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AEROACOUSTICS OF A POROUS PLUG JET NOISE SUPPRESSOR

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SUMMARY

The analytical and experimental investigation of the aeroacoustics of a Porous Plug Jet Noise Suppressor was initiated on January 1, 1981, under a NASA (Langley Research Center) grant #NAG-1-129 to Syracuse University.

The accomplishments of the period January 1, 1981 to June 30, 1981, are reported. The analytical design of an isentropic (contoured) external expansion plug-nozzle has been completed. The predicted flow features (such as streamlines; flow Mach number and pressure distributions) of isentropic plug-nozzles for different pressure ratios or exit flow Mach numbers; throat areas; ratios of the plug to annular nozzle radii; mass flow rates and the available run-times possible with the existing compressed air supply system, are compiled. The dimensions and the coordinates of the contour of typical isentropic external-expansion plugs with different exit flow Mach numbers, are listed. Based on these considerations the selection of an external-expansion isentropic plug-nozzle was finalized for fabrication for the proposed experimental aeroacoustic studies. These aeroacoustic data for an isentropic external-expansion plug-nozzle are to serve as the base-line acoustic and flow data for subsequent comparison of the aeroacoustic performance of a porous plug-nozzle to assess its effectiveness as a supersonic jet noise suppressor.

The needed modifications of the existing coaxial-jet compressed air facilitate, the use of the new supply chamber and the details of the assembly of the plug-nozzle have been designed. Some of the design details of the experimental facility and the plug-nozzle selected for experimental aeroacoustic studies are reported. The fabrication of the plug-nozzle and the needed modifications of the compressed air supply and pressure controls are underway.

The analytical flow prediction by the method of Characteristics of a Conical (non-contoured) Porous Plug-nozzle have been initiated. The aim of these analytical studies is to examine the role of the shape, the size and the porosity of the plug surface in achieving over a perforated conical (non-contoured) plug a nearly isentropic shock free supersonic flow field which is closely similar to the flow field of a contoured isentropic plug-nozzle.

SYMBOLS

A Cross-Sectional area

a Acoustic speed

K Ratio of the plug radius to the nozzle radius

L Axial length

$\dot{m}$ Mass flow rate

M Flow Mach number

p Static pressure

P_o Total pressure

r Radial length from the annular nozzle lip to the plug surface

R Radius

t Time

T Flow temperature

T_o Stagnation temperature

V Jet flow velocity

w_t Annular width or height at the throat

x Axial coordinate

y Radial coordinate perpendicular to x

Greek Symbols

ω Prandtl-Meyer angle

α Inclination angle between the nozzle wall and the nozzle axis

ρ_o Total (stagnation) density

μ Mach angle

γ Ratio of specific heats

ϕ Angle between $M = 1$ line and the Mach line from nozzle lip to the plug surface

ξ Pressure ratio $\frac{P_o}{P_a}$

Subscripts

a Ambient

e Nozzle exit

p Plug

n Nozzle

j Jet flow velocity

t Throat parameters

Superscripts

* Parameters where $M = 1$

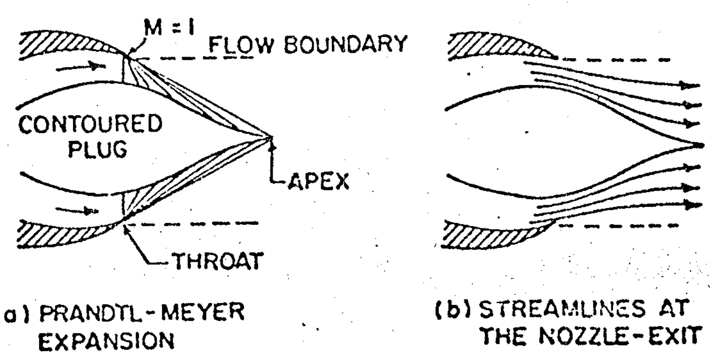
INTRODUCTION

It is common knowledge that the noise radiated by high speed turbulent heated exhaust flows of high specific thrust jet engines is very intense. Its suppression, therefore, is of considerable environmental interest. A successful abatement of such intense noise is bound to impact favorably on the development of any future high speed jet transport aircraft and/or rocket engines. The aerodynamic noise radiated by such exhaust flows is intense because of the high mean flow velocity V_j of the jet flow; high mean flow velocity gradients just downstream of the nozzle exit and the mixing and the turbulent nature of the heated exhaust flows. In an improperly expanded high speed jet flow or where solid objects are mounted in the supersonic jet flows, cellular repetitive shock structure is also present. The convection of flow (velocity; pressure; temperature) fluctuations through a shock front generates acoustic wave radiation which may either be the shock-associated broad-band noise and/or be the feed-back type screech noise. Therefore, to suppress successfully the aerodynamic noise radiated by supersonic jet flows, any promising and practical approach must result in some favorable modification of the exhaust flow such that the contributing noise-generating mechanisms and the more dominant noise sources noted above, are reduced in strength and effectiveness. Moreover in the process of achieving noise suppression from jet propulsion flow systems, it is imperative that the helpful modifications in the exhaust flows are achieved at a minimum and acceptable thrust and weight penalty.

To achieve this objective, a number of different supersonic jet noise suppression approaches, including the use of annular and co-annular plug nozzles, have been investigated in the past with varying success[2-6]. More recently Maestrello[7] has shown experimentally that at higher than the critical pressure ratios (supersonic flows), the use of a convergent nozzle with a porous cylindrical center-body and a tapered conical termination mounted along the nozzle-axis and stretched from the nozzle throat through most of the supersonic part of the exhaust flow, serves as an effective supersonic jet-noise suppressor. The geometrical configuration of this combination of the convergent nozzle with a long cylindrical center-body is somewhat similar to, but not quite the same, as a conventional plug nozzle.

Plug Nozzles

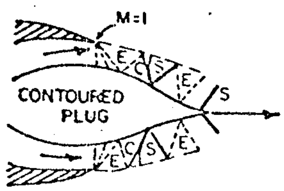
The plug-nozzle is a modification of a conventional C-D nozzle where the supersonic expansion is generally not confined within the solid walls of the nozzle. Instead the supersonic expansion (either in part or completely) occurs externally. The plug is designed such that at the design pressure ratio, the final expansion ray intersects the plug apex (see sketch below). The outer free boundary of the jet flow adjusts itself to the ambient conditions and the static pressure along the contoured plug surface decreases continuously from the throat pressure to the ambient pressure at the apex. The ideal contour of the axisymmetric plug can be computed by the method of characteristics. For a given plug configuration



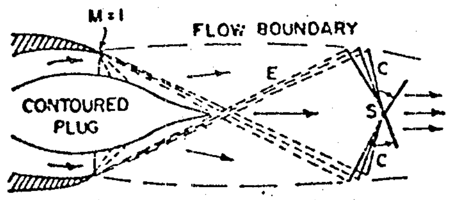
Flow Features of a Fully-expanded (isentropic) External Expansion Plug

and design pressure ratio, there exists only one plug-contour which does not introduce wave structure in the flow either over the plug and/or beyond the plug-apex. In addition beyond the plug-nozzle exit i.e. beyond the apex of the plug (see sketch on p. 2), the resulting flow is parallel to the plug-centerline. To achieve this, the flow at the nozzle throat must be directed inwards (towards the axis) so that at a given above-critical pressure ratio the flow turning produced by P-M expansion at the throat will yield axial flow at the plug apex. Such a contoured plug is often designated as an isentropic plug. The flow features of a contoured plug are illustrated on p. 2.

If a contoured plug nozzle were to be operated in the overexpanded mode i.e. with the back or the ambient pressure p_a higher than its design pressure ($p_a > p_e$), the final ray of the P-M expansion fan centered at the nozzle throat will intersect the plug at a point upstream of the plug-apex (see sketch below). The outer free-boundary of the jet flow will be directed inwards i.e. towards the plug axis. Because of the contour of the plug, further compressions and expansion waves will occur downstream of the point of incidence of the last ray of the P-M expansion and formation of shock front in the jet flow is possible. In turn, the passage of fluctuations of flow velocity, temperature and pressure through the shock fronts will generate additional shock-related noise.



Flow and wave pattern from a contoured plug-nozzle operated at below-design pressure ratio (over-expanded mode)



Flow and wave patterns from a contoured plug-nozzle operated at above-design pressure ratio (under-expanded mode)
E Expansion Rays
C Compression Rays
S Shock

At an operating back or ambient pressure lower than the design back pressure (the underexpanded mode), the aerodynamic performance of the contoured plug-nozzle is the same as for the design case and the pressure distribution along the contoured surface of the plug remains unaffected. However the flow continues to expand beyond the apex yielding a non-axial jet flow component. The flow boundary conditions along the axis and at the free-jet flow component. The flow boundary conditions along the axis and at the free-jet flow boundary will require wave structure downstream of the apex and shock structure in the flow downstream of the apex will result. Thereby the shock-related noise components will be generated. Therefore, if the optimization of both the aerodynamics and aeroacoustics performance was desired, the operation of the contoured plug at the design pressure ratio, yielding a shock-free flow in the axial direction, recommends itself. If however, the contoured external-expansion plug-nozzle is replaced by a solid uncontoured conical plug-nozzle, comparatively stronger reflected wave structure (shocks and shock cells) will be present in the supersonic flow over the plug as well as in the flow downstream of the plug-apex*. Also the flow streamlines may be directed at an angle to the plug centerline. As compared to an isentropic plug, such use of a conical (uncontoured) plug therefore will result in some deterioration of both the thrust performance and the flow field. Such flows are likely to radiate higher levels of the noise owing to the dominant shock-associated noise components.

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* If the plug-nozzle was to comprise a convergent nozzle with a solid cylindrical center-body of arbitrary length and conical termination, similar flow behavior will be expected.

Therefore, if for practical considerations, it is necessary to use a conical uncontoured plug of a reasonable half-angle, it is desirable to avoid its acoustic disadvantages by devising an approach which either weakens or eliminates the shock-structure normally present in such supersonic flows. To achieve this objective the adaptation of a porous stead of a solid plug as an integral component of a conical plug-nozzle, looks promising.

Porous Plug-Nozzle Noise Suppressor

The shadowgraphic records by Maestrello[7] of the supersonic underexpanded jet flow from a convergent nozzle with a perforated cylindrical center body* exhibit noticeable modifications (weakening) of the shock-structure in the underexpanded jet flow. The attendant reductions in the levels of the radiated noise were also observed.[7] In the original research proposal to NASA, the following underlying idea was advanced by the author of this report as a possible explanation of this observed weakening of the cellular wave structure.

The reflection of wave fronts (may these be compressions or expansions) incident either on a solid surface or a free flow boundary is inherently different. The flow over a solid surface follows the surface i.e. the flow direction (or the so-called θ condition) is to be satisfied, thus requiring that a compression front incident on the solid surface reflects as a compression and that an expansion front reflects as an expansion. On the other hand for a freely expanded jet flow, the pressure along the jet flow boundary is constant, and therefore, the so called p condition need to be satisfied along the jet free boundary. This requires that a compression front incident on the free jet flow boundary be reflected as an expansion and an incident expansion front be reflected as a compression. (See illustration on p. 6).

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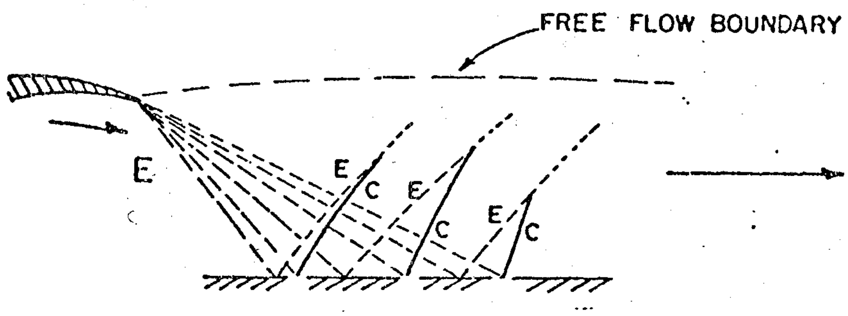
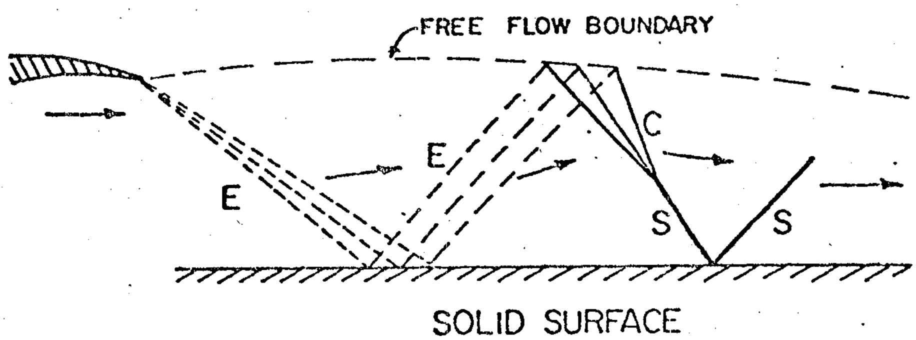
* This configuration of a convergent nozzle as combined with a cylindrical center-body appears to be geometrically similar to that of a conventional plug-nozzle. Yet it is not the same. In a conventional plug-nozzle an initial flow inclination at the nozzle throat (as dictated by the selected operating pressure ratio) is provided. This does not seem to be the case in the center-body plug-nozzle used by Maestrello[7].

Since successive compression fronts tend to coalesce and focus, the likelihood of the formation of a shock front exists. In the case of a solid plug, in an improperly expanded jet flow, the p condition applies at the free jet flow boundary and the θ condition at the solid surface of the plug. Therefore the



Porous (Plug) Surface
Reflected Expansions and Compressions Cancel



Reflected Expansions from the Solid (plug) surface reflect as compressions from the free flow boundary to form shock fronts.

E Expansions
C Compressions
S Shocks

different boundary conditions at the outer and the inner flow boundaries result in asymmetric reflections. Furthermore if a porous plug nozzle were to be used, over the porous plug surface both the θ and the p conditions need to be satisfied from the successive adjacent parts of the surface of the plug. Thus if the expansion rays of the Prandtl-Meyer fan originating at the nozzle throat lip were to impinge in sequence on the porous and the solid parts of the surface of the porous plug, the expansion rays will reflect as compressions and expansions respectively (see p.6). This opposite nature of the reflected waves results in the weakening and/or the cancellation of the waves and the focusing of the reflected compression wave fronts does not occur. Therefore, the usual shocks and the repetitive cellular wave structure in the plug-nozzle flow is either very much weekened in strength and/or under optimized design of porous plug-nozzle, may even be eliminated. The possibility that an uncontoured conical porous plug-nozzle operated over a wide range of pressure ratios may yield aerodynamic and aeroacoustic behavior which may be closely similar to that of a shock-free contoured plug-nozzle at or near its design pressure-ratio is a potentially attractive approach for jet noise suppression. Therefore the aim of the proposed study essentially boils down to: (a) how best to adapt and to optimize the design of a porous conical (uncontoured) plug so that it will modify an improperly expanded exhaust flow such that it attains features nearly similar to those of a flow over a contoured isentropic plug i.e. the exhaust flow is without shock structure and that its flow direction at the plug-apex is parallel to the plug centerline.

Very little information exists in the literature on the aeroacoustic performance of supersonic jet flows over a porous plug. Neither the basic gas dynamics of the porous plug elements designed to eliminate the shock structure in supersonic jet flow nor the aerodynamics (pressure distributions; mean flow direction; thrust and drag) of such a porous plug-nozzles have been studies before. Therefore the following aeroacoustic studies of a porous plug nozzle for supersonic jet noise suppression were proposed (for details of their scope and approach see the original proposal to NASA).

(a) Analytical prediction and optimization of the cancellation of the wave structure in an improperly expanded heated jet flow over a porous conical plug will be undertaken: the preferred porosity; length, contour and surface area of the porous plug needed to optimize the flow modifications so as to maximize noise reductions with minimal thrust penalty, will be deduced.

(b) The gas dynamics and the radiated noise of a porous conical uncontoured plug nozzle of the selected optimum design and configuration derived from (a) above, will be experimentally studied. The heated jet flows with total temperature upto $860^{O}K$ (1000^{0} F.) will be used for some of the studies. For comparison, the corresponding solid plug, keeping all other geometrical and operating parameters the same as used in the porous plug, will be investigated.

(c) Analysis and interpretation of the acoustic data and the identification of the dominant noise sources and their spatial distribution will be undertaken in conjunction with the gasdynamics of the supersonic flows over the nozzle-plugs of the selected design and configuration studied in (a) and (b) above.

(d) For comparison, aeroacoustic data will be gathered also for a contoured conical solid plug operated at its design pressure ratio. These aeroacoustic studies will provide the base-data for comparison of the aeroacoustic performance of the porous conical plug-nozzle. To achieve the objective of proposed studies, first the design of a contoured plug nozzle was undertaken.

External-Expansion Isentropic Plug-Nozzle

In an external-expansion plug nozzle (see sketch on p. 10), a centered Prandtl-Meyer expansion emanates from the nozzle-lip P . The flow turning angle ω by the centered isentropic expansion (the Prandtl-Meyer angle) is given by:

$$\omega = \sqrt{\frac{\gamma+1}{\gamma-1}}\, \tan^{-1}\sqrt{\frac{\gamma-1}{\gamma+1}(M^2-1)} - \tan^{-1}\sqrt{M^2-1} \tag{1}$$

where for $M = 1$, $\omega = o$.

For isentropic flow, the pressure ratio, area ratio and the flow Mach number are related by:

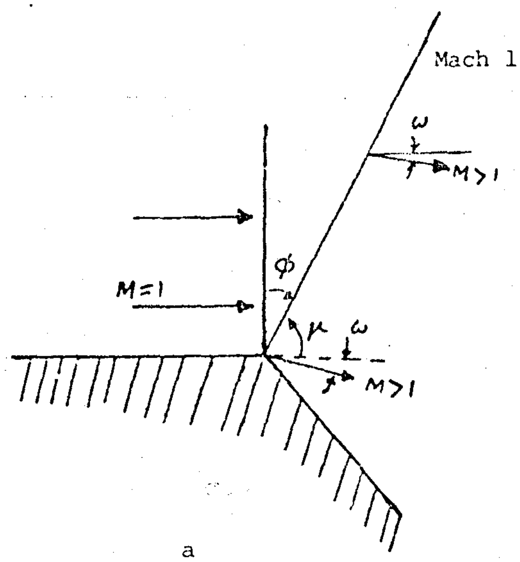
$$\frac{P_o}{p} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} \tag{2}$$

where the total Pressure P_o is constant.

$$\frac{A}{A^*} = \frac{1}{M}\left[\frac{2}{\gamma+1}\left(1 + \frac{\gamma-1}{2} M^2\right)\right]^{\frac{\gamma+1}{2(\gamma-1)}} = \frac{\rho^* V^*}{\rho V} \tag{3}$$

By Eliminating M from relations 2 and 3,

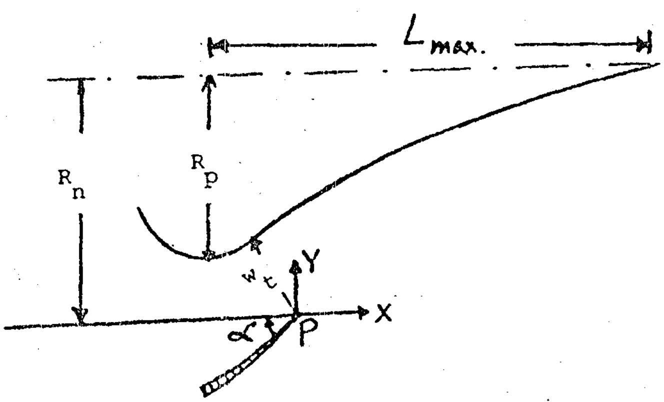
$$\frac{A}{A^*} = \frac{\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \left(\frac{\gamma-1}{2}\right)^{1/2}}{\left[\left(\frac{p}{P_o}\right)^{\frac{2}{\gamma}} - \left(\frac{p}{P_o}\right)^{\frac{\gamma+1}{\gamma}}\right]^{1/2}} \tag{4}$$



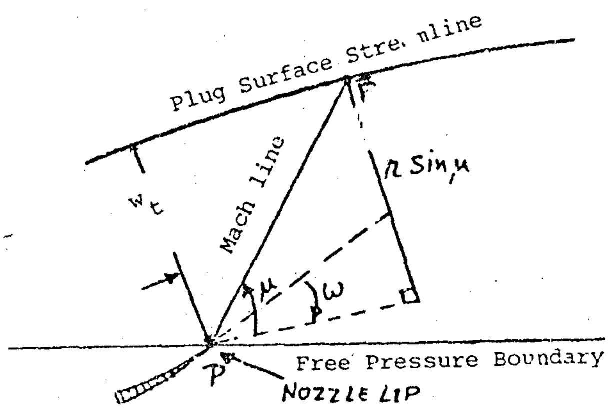
a

$$\phi = \frac{\pi}{2} - \mu + \omega$$

Mach line Location with
respect to M = 1 line.



b



c

Fig. 1. Nomenclature of External-Expansion Plug-Nozzle Geometry and Flows.

Also $\omega = \phi + \mu - \frac{\pi}{2}$ (see sketches in Fig. 1 on p.10)

$$\mu = \sin^{-1}\frac{1}{M} \tag{5}$$

Therefore

$$\phi = \sqrt{\frac{\gamma+1}{\gamma-1}}\ \tan^{-1}\sqrt{\frac{\gamma-1}{\gamma+1}(M^2-1)} \tag{6}$$

If a design pressure ratio or exit flow Mach number at the apex of the plug is specified, then the P-M centered expansion fan at the nozzle lip (at the throat section with $M = 1$ and $\phi = o$) expands the flow to the design exit Mach number and turns it through angle ω. If the expanded flow over the contoured plug were to be directed along the axis of the plug-nozzle, then the annular nozzle surface should be inclined by the same angle in the opposite direction such that the centered P-M expansion re-directs the flow at the throat to an axial direction at the apex of the plug.

To obtain the contour of external-expansion isentropic plug, the individual Prandtl-Meyer rays (Mach-lines) are assumed not to reflect at the plug surface. The plug surface is taken to be a streamline. The expanded free jet flow boundary is also a streamline. At the throat, $M = 1$, Mach angle $\mu = 90^{\circ}$, $\phi = o$; and $\omega = o$. For any Mach line of radial length r and angle ϕ (see sketch c in Fig.1) a mass balance is affected between the plug throat section and the cross-sectional area at a given location at the plug surface[8,9].

Mass flow rate $\dot{m} = \rho VA =$ constant

Therefore the mass balance at the throat ($M=1$) and across a Prandtl-Meyer ray from the nozzle lip P and point $\bar{P}$ on the plug contour

$$\rho_t V_t w_t = \rho V r \sin\mu \tag{7}$$

where w_t is the width or height of the annulus at the throat

Using isentropic flow relations,

$$\frac{r}{w_t} = \left(\frac{a_t}{a}\right)^{\frac{\gamma+1}{\gamma-1}}$$

Since for isentropic flows T_o , the stagnation temperature, is constant

$$\frac{r}{w_t} = \left[\frac{T_t}{T_o} \left(\frac{T}{T_o} \right)^{-1} \right]^{\frac{\gamma+1}{2(\gamma-1)}}$$

$$\frac{r}{w_t} = \left[\frac{2}{\gamma+1} \left(1 + \frac{\gamma-1}{2} M^2 \right) \right]^{\frac{\gamma+1}{2(\gamma-1)}} \qquad (8)$$

At the throat section of the plug-nozzle $r/w_t = 1$ on the plug surface. Using relation 8 and selecting flow Mach number increments between the initial flow Mach number M = 1 and the design flow Mach number M_e at the nozzle exit at the plug apex, the plug-surface streamline or plug contour can be predicted. Given different design exit Mach numbers, a family of plug contours can be obtained from relation 8. Fig. 2 shows plug contours for M_e = 1.2, 1.3, 1.37, and 1.5. For each design exit Mach number or pressure ratio, there is only one plug contour which yields isentropic flow. The higher the design Mach number, the longer is the plug. Using relation 8 and taking increments of $\frac{r}{w_t}$ between 0 (at nozzle lip P) and 1 (on the plug surface on M = 1 line), the plug contour and the streamline of the flow field can also be mapped for any isentropic plug. Streamlines for the M = 1.37 and M = 1.5 isentropic plugs are presented in Fig. 3a.

The Mach lines of the plug-nozzle flow at selected design pressure ratios are presented in Fig. 3b. The initial (M=1) line is taken to be perpendicular to the plug surface. The last Mach line emanating from the annular nozzle lip P is terminated at the plug apex such that the turning of the flow across it results in axial flow at the exit.

The distribution of the flow Mach number and the pressure ratio p/p_o along the plug surface are shown in Figs. 4 and 5. The flow Mach number increases and the local static pressure decreases along the plug surface. The static pressure ratio p/p_a and the static pressure p along the contoured plug surface are shown in Fig. 6. It is worth noting however that the local static pressure along the plug surface is higher than the ambient pressure of the surrounding medium. Since the total pressure is constant, for choked flow at the nozzle throat, the static pressure decreases from pressure $p \doteq 0.528p_o$ to the ambient pressure at the nozzle

exit (i.e. at the plug apex). For subsequent analytical modelling of the porous conical plug flow and its prediction by the method of characteristics, this higher than the ambient flow pressure along the plug surface, will be an important consideration.

Non-dimensional flow properties and geometrical parameters of isentropic external-expansion plug-nozzles at different design flow Mach numbers are given in Tables 1-4. The goemetrical specifications and flow parameters of two external-expansion plug nozzles, both designed for $M_e = 1.37$, are presented in tables 5 to 10. The annular throat areas of two nozzles are equivalent to those of a 3.175 cm (1.25") and 4.445 cm (1.75") diameter round nozzles respectively. For each of the plug nozzles, ratios K of plug radius R_p to nozzle radius R_n of 0.2, .5 and 0.9 were considered. The coordinates of the plug contours for $M_e = 1.5$ and different K's are given in Tables 11-16.

For each design exit-flow Mach number (or design pressure ratio), the ratio of the maximum plug length to the annular nozzle width, x_{max}/w_t or L_{max}/w_t is constant for any ratio of the plug radius to the nozzle radius K (see Tables 5 to 10 for $M_e = 1.37$). However, by selecting plug nozzles of different K's and thus changing the annular nozzle width $w_t = R_n - R_p$, contoured plugs of different maximum length can be obtained for each design-exit flow Mach number. The geometrical specifications and flow parameters for a plug-nozzle designed for $M_e = 1.37$ and throat area equivalent to that of a 3.1755 cm round nozzle are listed in Tables 5 and 6. For $M_e = 1.37$ and each of the two values of $K = 0.2$ and 0.5, L_{max}/w_t or $x_{max}/w_t \doteq 1.03$. For the nozzle with the same throat area, a smaller K means a smaller annular width.

The ratio of the maximum length, L_{max}, of the contoured plug to the annulus-height w_t at the throat (L_{max}/w_t) as a function of the exit-flow Mach number is presented in Fig. 7. With increasing-exit-flow M_e Mach number, the ratio L_{max}/w_t increases; for example for $M_e = 1.37$, $L_{max}/w_t = 1.03$ and $M_e = 1.5$, $\frac{L_{max}}{w_t} = 1.32$

A matrix of plug-nozzles of different throat areas and ratios of plug-radius to

annular nozzle radius K ranging from 0.1 to 0.9 have been calculated (see tables 5 to 19). The acutal dimensions of the plug nozzle configuration, i.e. R_p, R_n, w_t for a given throat area A_t and ratio K, are presented. Based on these considerations, the maximum length of the isertropic external-expansion plug nozzles can be varied in the following ways:

(a) For a given design exit flow Mach number and throat area, L_{max}/w_t = constant (Fig.7). Changing K values, results in different annular width w_t. Hence for the same exit flow Mach number and different K's, plugs of different maximum lengths are predicted. With $A^* = 7.9173$ cm^2 (equivalent to the exit area of a 3.175 cm diameter round nozzle) and $M_e = 1.37$, the maximum plug length L_{max} for different K's are listed below.

M_e	L_{max}/w_t	K	L_{max} (cm)
1.37	1.03	0.2	4.68
1.37	1.03	0.5	3.7
1.37	1.03	0.9	1.65

(b) For a given throat area A* and K, i.e. for the same w_t, the maximum lengths L_{max} of the plugs designed for higher exit-flow Mach numbers, M_e, will be longer (see Fig. 7). For different exit flow Mach numbers, different annular-nozzle wall inclinations will be required.

One of these typical isentropic external-expansion plug nozzles designed to be operated at (1) a selected ratio of the reservoir to ambient pressure ξ and (2) a selected K is to be machined shortly. The coordinates of such plug contours are summarized in Tables 5a; 8a; 11(a), 14(a).

The mass flow rates for each of these plug nozzles operated at a range of pressure ratios were also calculated. For the maximum (choked) mass flow rate of a given nozzle, the run-times were calculated for the available compressed air system. The nozzle dimensions and the operating pressure ratios were selected so that a reasonable run-time for recording the aeroacoustic data will be available. For example, a plug nozzle with throat-area $A^* = 7.9173$ cm^2 (equivalent to that of a 3.175 cm exit diameter round nozzle) would have a mass flow rate of 0.573 Kg/sec (1.264 lbm/$_{sec}$) and a run-time t = 36.6 minutes for a design pressure ratio, $\xi = 3.04$ i.e. design exit-flow Mach number $M_e = 1.37$. For further details on the air supply system, see Appendix A, p. 17 under Available Compressed Air Supply and Pressure Controls.

Relative location of Annular Nozzle Throat and the Nozzle Lip

The isentropic external-expansion plug contours predicted by the method of the cancellation at the plug-surface of the reflection of the Prandtl-Meyer expansion rays from the annular nozzle lip, hold true downstream of the initial sonic (M=1) line which is assumed to be located at the minimum area (or throat) section of the plug-nozzle. The plug-hump (Fig. 1c) can be located either at the nozzle minimum (throat) area section or upstream of it. The relative location of the plug-hump and the throat section is quite important for the gas dynamical considerations and the aerodynamic performance of this type of plug nozzle. This is so because the thrust coefficient decreases due to the expansion around the plug-hump which results in lower pressures on the plug surface.[10] Hence in the final configuration and fabrication of the external-expansion plug nozzle to be used for these aeroacoustic studies, the throat of the plug-nozzle and the annular nozzle lip (point P in Fig. 1c) will be located at the section where the curved surface of the hump of the plug becomes tangent to the contoured surface of the plug.

The prediction of the contour of a similar isentropic external-expansion plug by directly using the method of characteristics is in progress where instead of a straight perpendicular initial line, (1) a circular (2) a parabolic initial (M=1) lines will be also considered. The plug contours predicted by the wave cancellation method and those by the direct characteristic method will be compared. Should any differences between the two plug contour-coordinates be judged to be more than the expected machining tolerance, adjustments in the coordinates of the plug contours will be made for the fabrication of the plugs. Moreover the prediction of the isentropic plug contours and the distribution of flow properties in flow field of the plug nozzle directly by the method of characteristics is to serve as the basis and guide for the modelling under appropriate boundary conditions, analysis, and the prediction of flows and wave structure over conical porous plug-nozzles.

From considerations of the supersonic flow theory, the selection of the design (exit) flow Mach number M_e , the fixing of the sonic line of the initial flow Mach number M_t and the location of nozzle lip (point P), determine the initial (throat) to exit-area ratio and the inclination of the outer annular nozzle wall (the initial flow inclination).

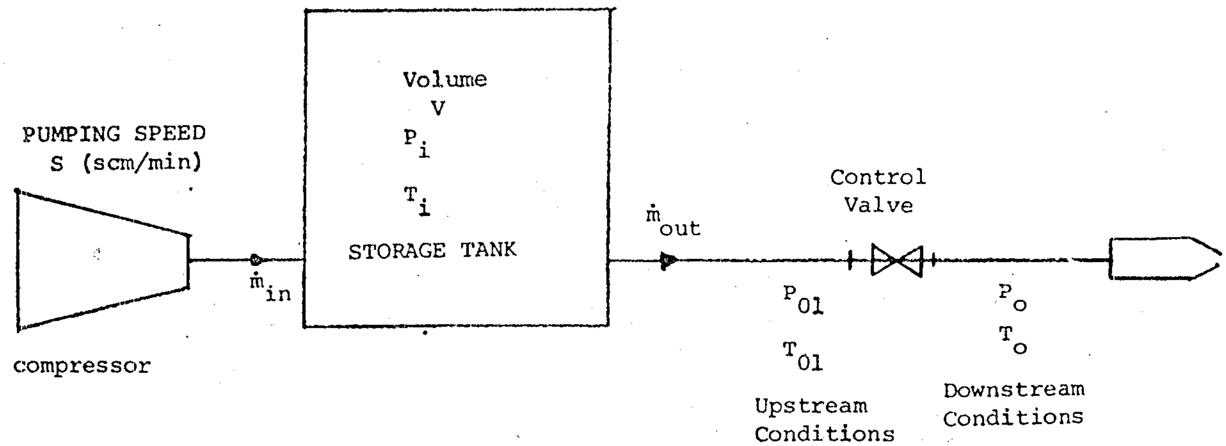
For the selected operating pressure ratio $p/_{p_o}$ (or the design flow Mach number M_e), the nozzle wall inclination angle α (see sketch p. 10) should be opposite and equal to the total flow turning Prandtl-Meyer angle ω_e such that the inclined flow at the throat is redirected parallel to the nozzle axis at the nozzle exit (see Fig. 2). Hence higher the pressure ratios, steeper the initial inclination of the outer wall of the annular nozzle need to be to obtain an axial flow at the exit of the plug.

Appendix A

Available Compressed Air Supply and Pressure Controls

The layout of the compressed air system is shown in Figs. A1 and A2. The compressed air is supplied by a Worthington HB-2 two-stage oil-less reciprocating air compressor, pumping capacity 7.9 scm/min. (279 scf/min) and the maximum discharge pressure of 3.435×10^6 N/m^2 (500 psig). The compressed air is cooled, dried and stored in five tanks of total capacity 31.15 m^3 (1100 cu.ft.). A reducer valve maintains air pressure at 1.03 1.03×10^6 N/m^2 (150 psig) in the 10.16 cm (4") diameter, 45.72 m (150 ft.) long supply line between the storage tanks and the jet room in the acoustic facility. From the storage tanks, the compressed air is supplied to the jet plenum chamber either directly or alternately via the 200 KW electric heater depending on whether respectively the investigations with the cold or the heated flows are to be undertaken. The stored compressed air is exhausted in the blow-down mode with either the compressor running or shutdown. Upstream of the jet supply chamber, pressure control valves and pressure regulators are provided to maintain the supply chamber stagnation pressure at a constant pre-selected value. Currently a 2.54 cm pressure control valve is operated in the compressed air supply line which, as is shown later, permits the use of a plug-nozzle with throat area equivalent to that of a 3.175 cm (1.25") diameter round convergent nozzle at a pressure ratio $\xi \doteq 3.3$ with run-time $\Delta t \doteq 33$ minutes. For the same nozzle but operated at lower pressure ratios, longer runtimes are available.(Table 21).

However to accomodate plug-nozzles with larger throat areas, an additional two-inch control valve is to be installed. This will permit the use of a plug-nozzle with exit area equivalent to that of 4.445 cm (1.75") diameter round nozzle. It will be possible to operate this plug-nozzle at pressure ratio $\xi \doteq 4.0$ with available run-time of about 11 minutes (see Table 23). For the same nozzle but at lower pressure ratios, longer run-times will be available. Some of the background details of the calculations of the mass flow rates at a range of operating pressures and the available run-times follow.



Mass balance for tank:

$$\dot{m}_{in} - \dot{m}_{out} = \frac{d}{dt}(\rho_i V) = V\frac{d}{dt}\left(\frac{P_i}{RT_i}\right)$$

$$\dot{m}_{in} = \rho_{std} S$$

where $\rho_{std} = 1.201\ kg/m^3$ (.075 lbm/ft^3)
and S is
the Pumping Speed

$\dot{m}_{out} = \dot{m}_c$ = Critical mass flow for choked conditions

T_i Stagnation Temperature in the Storage tank

$$\therefore \quad \frac{dP_i}{dt} = \frac{RT_{01}}{V}\left(\rho_{std} S - \dot{m}_c\right)$$

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The maximum mass flow of air for a choked nozzle is given by:

$$\dot{m}_c = \sqrt{\gamma}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \frac{P_o A^*}{\sqrt{R T_o}}$$

Using SI units and $\gamma = 1.4$

$$\dot{m}_c = 0.685 \frac{P_o A^*}{\sqrt{R T_o}} \quad \text{Kg/sec} \qquad \text{A-1}$$

The volume flow rate through a control valve for a given pressure difference, ΔP, is given by:

$$Q = \sqrt{\frac{520}{G T_{o1}}}\, C_g P_{o1} \sin\left(\frac{3417}{C_1}\sqrt{\frac{\Delta P}{P_{o1}}}\right) \quad \text{scm/hr}$$

where the specific gravity G of air = 1 and C_g and C_1 are the valve coefficients as given by the manufacturer (Fisher Controls). The mass flow relation is given by:

$$\dot{m} = \rho_{Std.} Q \quad \text{Kg/sec}$$

<u>Max.</u>	$P_{o1} = 961.90$ kN/m^2 (140 psig)	$P_o = 82.45$ kN/m^2 (12 psig)	equal to reservoir pressure
<u>Min.</u>	$P_{o1} = 412.24$ kN/m^2 (60 psig)	$P_o = 309.18$ kN/m^2 (45 psig)	

Knowing P_{o1}, P_o, $\Delta P = P_{o1} - P_o$ and the valve coefficients C_1, C_g the volume flow rate, Q, is calculated and from which the maximum mass flow for a given ΔP is found. Using relation A-1 for a choked nozzle, the critical mass flow, $\dot{m}_c$, for different reservoir pressures, P_o, can be computed. This mass flow

rate is compared with the mass flow rate $\dot{m}$ the pressure control valve can supply at ΔP. Obviously for successful operation, it is necessary that $\dot{m}_c \leq \dot{m}$. The critical mass flow rate $\dot{m}_c$ in (A-1) is found by selecting an A* of the plug-nozzle and then varying the reservoir operating pressures (Tables 20 to 23).

The available run-time is defined as the time interval $\Delta t = t - t_o$ it will take for the storage tank pressure to drop just to the cut-off value upstream of the control valve such that the needed flow rate required at the operating conditions of the nozzle cannot be maintained through the control valve. Using the mass balance relation with the compressor running

$$\frac{dP_i}{dt} = \frac{R T_{01}}{V} \left(\rho_{std.} S - \dot{m}_c \right)$$

and integrating it from $t = 0$ to $t = \tau$, the following relation for the run time $\Delta t = \tau$ is obtained

$$\tau = \frac{V(P_i - P_{01})}{R T_{01} \left(\dot{m}_c - \rho_{std} S \right)} \quad \text{sec.}$$

If the compressor is shut off, then $S = 0$ and Δt will be shorter.

The run-time Δt calculated for the 2.54 cm control valve for plug nozzles with throat areas equivalent to that of 2.54 cm and 3.175 cm diameter round jets respectively in Tables 20-21. For a 2.54 cm equivalent round jet plug nozzle, the run-times are long enough for the entire range of possible pressure ratios and the acoustic data at all the eight survey locations could be recorded with relative ease during the same run. A plug-nozzle with a throat area equivalent to 3.175 cm diameter round nozzle presents some available run-time problems at the higher pressure ratios.

This is because the one-inch control valve can not supply the needed mass flow to maintain choked flow at higher pressure ratios through the plug nozzle. Operation is only possible when pressure ratios are kept equal to or less than $\xi = 3.26$, giving a run-time of 33.48 min.

A modification of the present air supply system is planned where in addition to the 2.54 cm control valve, also a 5.08 cm control valve is to be installed. This will allow higher mass flow rates hence the use of larger plug-nozzle throat areas will be possible for reasonable run-times (see Tables 22 and 23) For this bigger control valve, a plug nozzle with throat area equivalent to that of round nozzle of diameter 4.445 cm can be operated at the pressure ratios ξ upto 4.1 or even higher. From Tables, 20 to 23, the use of plug nozzles with throat areas equivalent to those of 3.175 cm and a 4.445 cm diameter round nozzles is compatible with the existing compressed air supply with a 5.08 cm (2") pressure control valve to be installed.

Plenum Chamber Design

The existing plenum chamber which has been used previously for a concurrent operation of three-nozzle coaxial jet flows, will be modified for the proposed aero-acoustics studies of the plug-nozzle flows. The existing plenum chamber if it were to be used directly for plug-nozzle studies presents (a) plug mounting problems. The existing chamber will have to be cut to mount the needed plug holder. However if instead the settling chamber of the second coaxial jet were to be used as a settling chamber for the plug-nozzle when the innermost nozzle outlet is used as the plug holder, then (b) the settling chamber may not be large enough to provide the required well-settled flow at the needed mass flow rates at higher pressure ratios and larger throat areas.

From the above reasons, it was decided to design a new plenum chamber for the plug-nozzle to be coupled to the existing compressed air supply system. The new plenum chamber (Figs A3 and A4) incorporates a removable plug holder, a replaceable annular nozzle to accomodate nozzles with different design exit flow Mach numbers. Wire gages (screens) downstream of the plug holder will be used to straighten turbulent flow due to the stem for holding the plug. Pitot-static and thermocouple probes will be installed for pressure and temperature measurements respectively. The plug itself would have static pressure holes on the plug

surface for surface flow pressure measurements. Some of the specifications of the new plenum chamber are:

Diameter = 30.48 cm (12"), overall length = 76.20 cm (30")

Cross sectional area of the chamber = 729.66 cm^2

Annular Throat area of the plug-nozzle
7.92 cm^2 - equivalent to that of a 3.175 cm round nozzle
15.52 cm^2 - equivalent to that of a 4.445 cm round nozzle

$$\frac{\text{Cross sectional area of the chamber}}{\text{Annular throat area}} = \begin{array}{l} 92:1 \text{ for annular throat area} = 7.92\ cm^2 \\ 47:1 \text{ for annular throat area} = 15.52\ cm^2 \end{array}$$

These area ratios will ensure low speed flows in the chamber.

The plenum-chamber is to be fabricated from stainless steel and thus will be suitable for operation at $T_o \doteq 810^{o}K$ (1000^{o} F) with the plug-nozzle operated at pressure ratio ξ upto 4.0.

The plenum chamber is to be insulated all around to prevent heat loss and to avoid acoustic reflection. Also, this plenum chamber could be easily removed if any future studies on the three coaxial nozzle jet system were to be undertaken.

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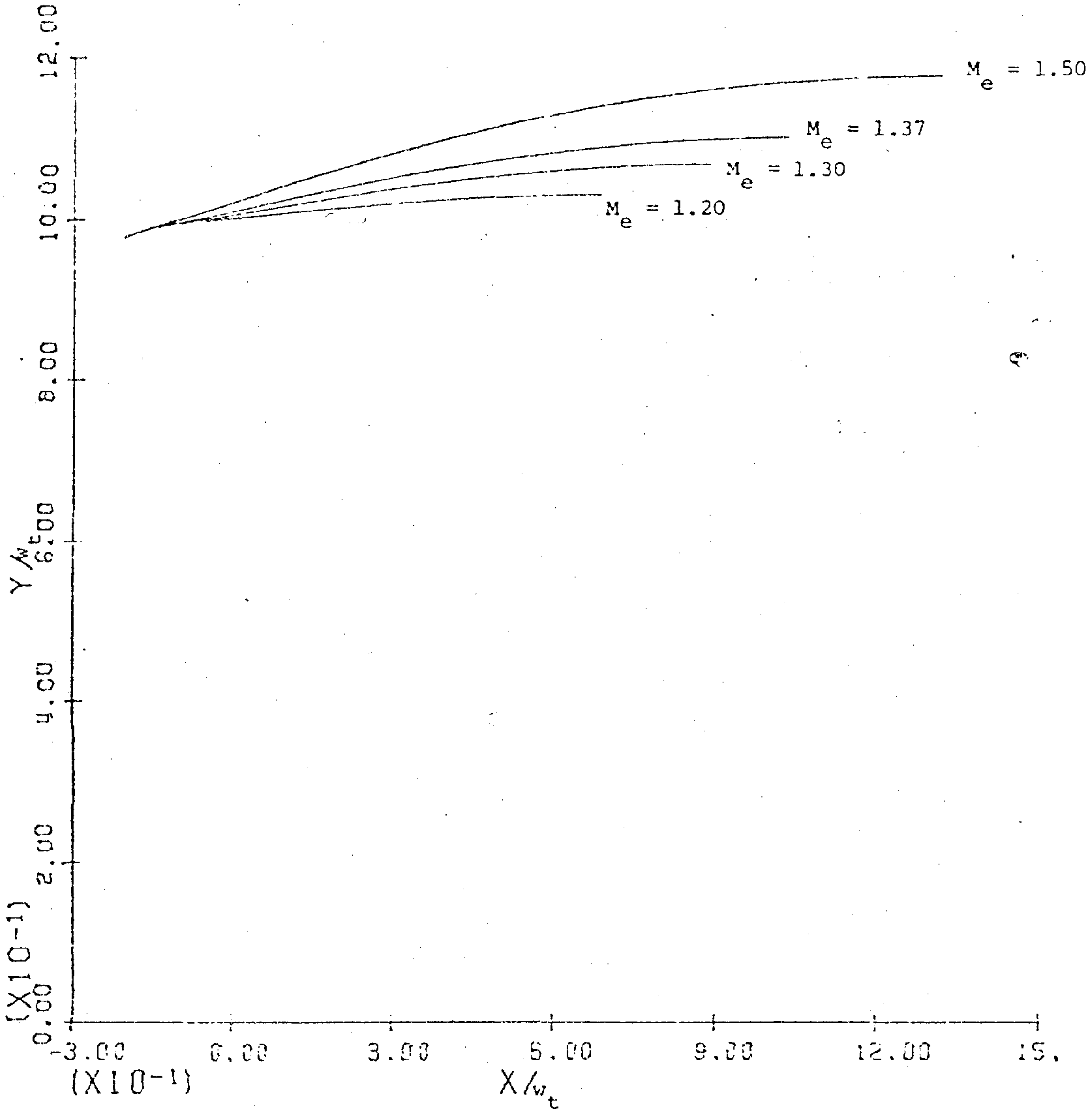
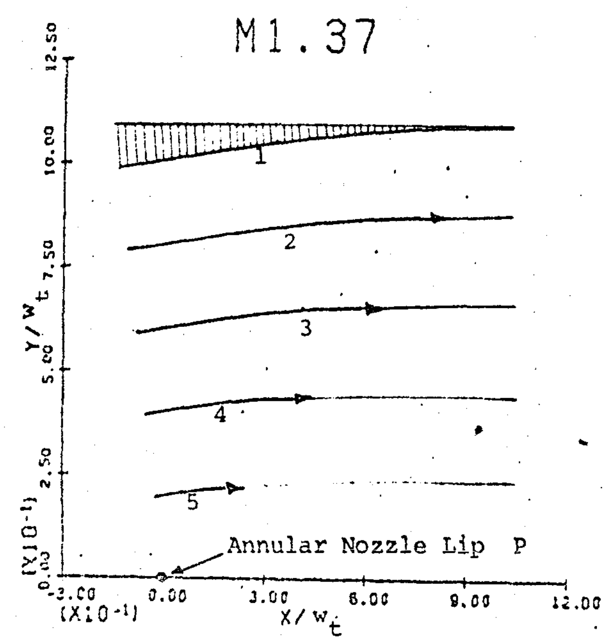
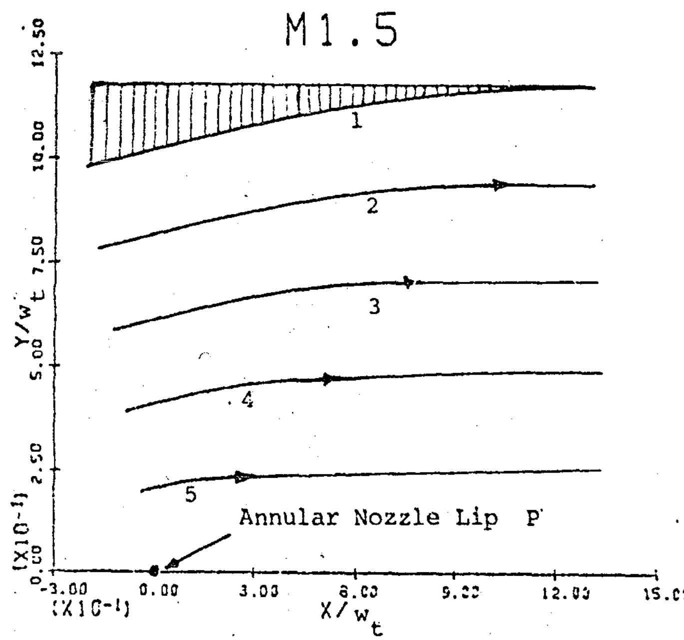


Fig. 2 Isentropic Plug Nozzle Contours for Different Design Flow Mach Numbers.





EXIT MACH NUMBER: 1.37

Exit ω : 8.120°

No	M	X/w_t	Y/w_t	X/w_t	Y/w_t	X/w_t	Y/w_t	X/w_t	Y/w_t	X/w_t	Y/w_t
1	1.000	-0.1414	0.9900	-0.1131	0.7920	-0.0040	0.5940	-0.0566	0.3960	-0.0283	0.1980
2	1.019	[illegible]	1.0175	0.0415	0.8140	0.0312	0.6105	0.0208	0.4070	0.0104	0.2035
3	1.037	0.1262	1.0292	0.1094	0.8234	0.0817	0.6175	0.0545	0.4117	0.0272	[illegible]
4	[illegible]	0.2030	1.0383	0.1430	0.8307	0.1223	0.6230	0.0815	0.4153	0.0409	0.2077
5	1.074	[illegible]	1.0451	0.1197	0.8267	0.1509	0.6276	0.1055	0.4184	0.0527	0.2092
6	[illegible]	[illegible]	[illegible]	0.2345	0.8423	0.1969	0.6317	0.1273	0.4212	0.0636	0.2106
7	1.111	[illegible]	1.0570	[illegible]	0.8472	0.2220	0.6354	0.1400	0.4236	0.0749	0.2118
8	[illegible]	0.4194	1.0646	0.3527	0.8517	0.2519	0.6388	0.1670	0.4250	0.0835	0.2127
9	1.148	[illegible]	1.0697	[illegible]	0.8557	0.2867	0.6418	0.1871	0.4279	0.0936	0.2139
10	1.166	0.5151	1.0743	0.4121	0.8574	0.3091	0.6446	0.2061	0.4297	0.1030	0.2149
11	[illegible]	0.5613	1.0785	0.4494	0.8620	0.3371	0.6471	0.2247	0.4314	0.1124	0.2157
12	1.204	[illegible]	1.0823	0.4864	0.8659	0.3647	0.6494	0.2432	0.4329	0.1216	0.2165
13	1.222	[illegible]	1.0857	0.5232	0.8686	0.3924	0.6514	0.2616	0.4343	0.1308	0.2171
14	1.241	[illegible]	1.0885	0.5599	0.8710	0.4200	0.6533	0.2800	0.4355	0.1400	0.2170
15	1.259	0.7470	1.0914	0.5960	0.8731	0.4476	0.6547	0.2984	0.4365	0.1492	0.2183
16	[illegible]	[illegible]	1.0937	0.6333	0.8750	0.4753	0.6562	0.3169	0.4375	0.1584	0.2187
17	1.296	[illegible]	1.0956	0.6710	0.8765	0.5032	0.6573	0.3355	0.4382	0.1677	0.2191
18	[illegible]	[illegible]	1.0971	0.7085	0.8777	0.5313	0.6582	0.3542	0.4383	0.1771	0.2194
19	1.333	[illegible]	1.0981	0.7463	0.8785	0.5597	0.6589	0.3732	0.4393	0.1866	0.2196
20	1.352	0.9107	1.0988	0.7846	0.8790	0.5884	0.6593	0.3923	0.4395	0.1961	0.2190
21	1.370	1.0292	1.0990	0.8233	0.8792	0.6175	0.6594	0.4117	0.4396	0.2056	0.2190

|← 1 →|← 2 →|← 3 →|← 4 →|← 5 →|

EXIT MACH NUMBER: 1.5

EXIT ω : 11.91°

No	M	X/w_t	Y/w_t	X/w_t	Y/w_t	X/w_t	Y/w_t	X/w_t	Y/w_t	X/w_t	Y/w_t
1	1.000	-0.2063	0.9705	-0.1650	0.7020	-0.1236	[illegible]	-0.0825	[illegible]	-0.0413	[illegible]
2	1.025	0.0170	1.0254	0.0136	0.8203	0.0102	0.6152	0.0068	0.4102	0.0034	0.2052
3	1.050	0.1161	1.0457	0.0929	0.8366	0.0697	0.6274	0.0464	0.4183	0.0232	0.2091
4	1.075	0.1969	1.0617	0.1575	0.8494	0.1181	0.6370	0.0788	0.4247	0.0394	0.2123
5	1.100	0.2692	1.0755	0.2153	0.8604	0.1615	0.6453	0.1077	0.4302	0.0538	0.2151
6	1.125	0.3367	1.0879	0.2694	0.8703	0.2020	0.6527	0.1347	0.4351	0.0673	0.2176
7	1.150	0.4015	1.0990	0.3212	0.8792	0.2409	0.6594	0.1606	0.4396	0.0803	0.2195
8	1.175	0.4646	1.1093	0.3714	0.8874	0.2787	0.6656	0.1858	0.4437	0.0929	0.2219
9	1.200	0.5267	1.1187	0.4214	0.8950	0.3160	0.6712	0.2107	0.4475	0.1053	0.2237
10	1.225	0.5884	1.1275	0.4707	0.9020	0.3531	0.6765	0.2354	0.4510	0.1177	0.2255
11	1.250	0.6502	1.1355	0.5201	0.9084	0.3901	0.6813	0.2601	0.4542	0.1300	0.2271
12	1.275	0.7122	1.1428	0.5697	0.9143	0.4273	0.6857	0.2849	0.4571	0.1424	0.2286
13	1.300	0.7743	1.1495	0.6198	0.9196	0.4649	0.6897	0.3099	0.4598	0.1550	0.2299
14	1.325	0.8381	1.1555	0.6705	0.9244	0.5028	0.6933	0.3352	0.4622	0.1676	0.2311
15	1.350	0.9023	1.1607	0.7219	0.9286	0.5414	0.6964	0.3609	0.4643	0.1805	0.2321
16	1.375	0.9677	1.1653	0.7741	0.9322	0.5805	0.6992	0.3871	0.4661	0.1935	0.2331
17	1.400	1.0342	1.1691	0.8274	0.9353	0.6205	0.7015	0.4137	0.4676	0.2068	0.2338
18	1.425	1.1021	1.1721	0.8817	0.9377	0.6613	0.7033	0.4408	0.4688	0.2204	0.2344
19	1.450	1.1715	1.1743	0.9372	0.9395	0.7029	0.7046	0.4686	0.4697	0.2343	0.2349
20	1.475	1.2424	1.1757	0.9939	0.9406	0.7454	0.7054	0.4970	0.4703	0.2485	0.2351
21	1.500	1.3150	1.1762	1.0520	0.9409	0.7890	0.7057	0.5260	0.4705	0.2630	0.2352

|← 1 →|← 2 →|← 3 →|← 4 →|← 5 →|

Fig. 3a. Flow Streamlines for External-Expansion Plug-Nozzle at Different Design Flow Mach Numbers.

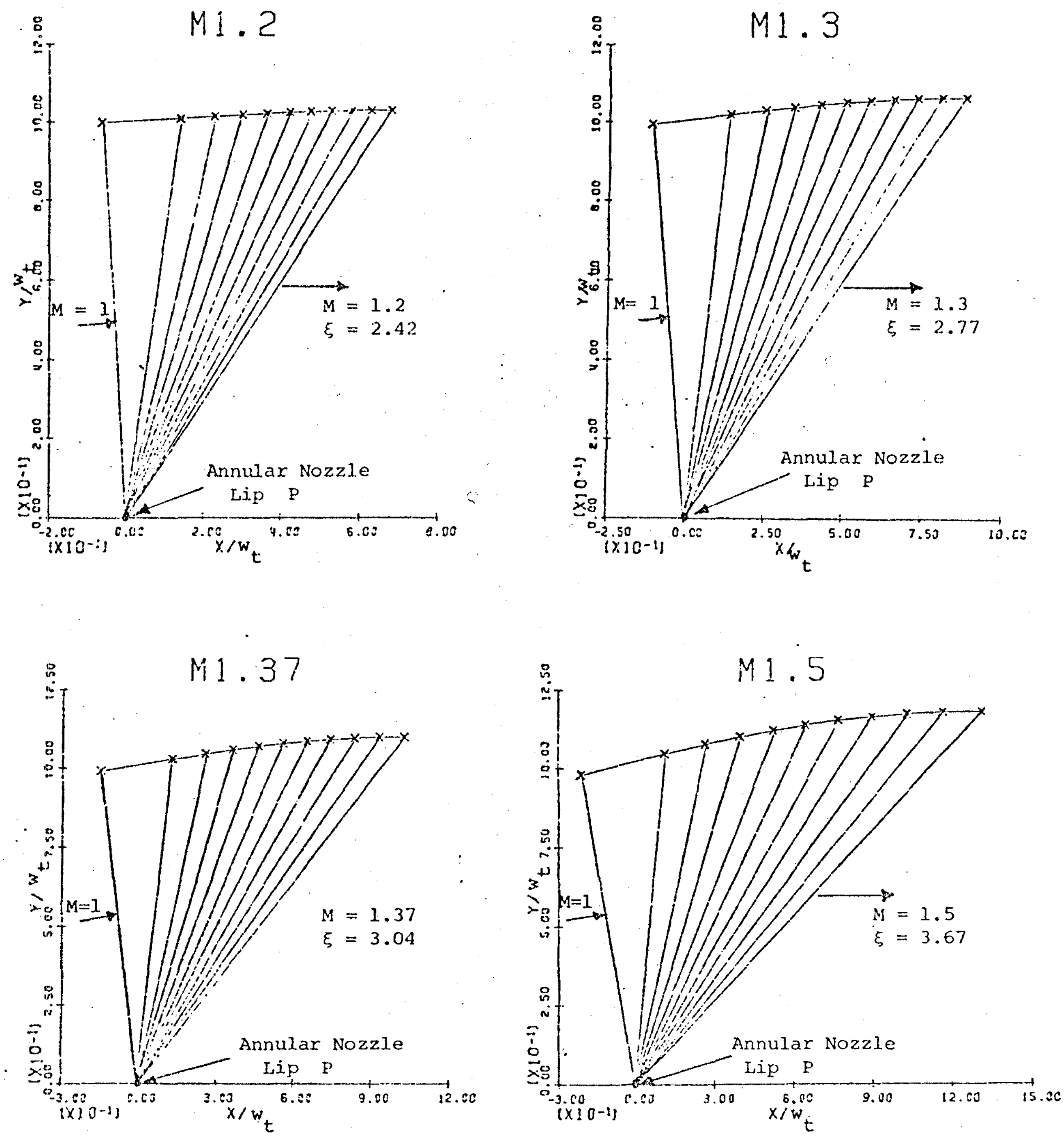


Fig. 3b. Mach Lines for Different Isentropic Plug Nozzles at Selected Design Flow Mach Numbers or Pressure Ratios (For Coordinates see Table 1-4 p.

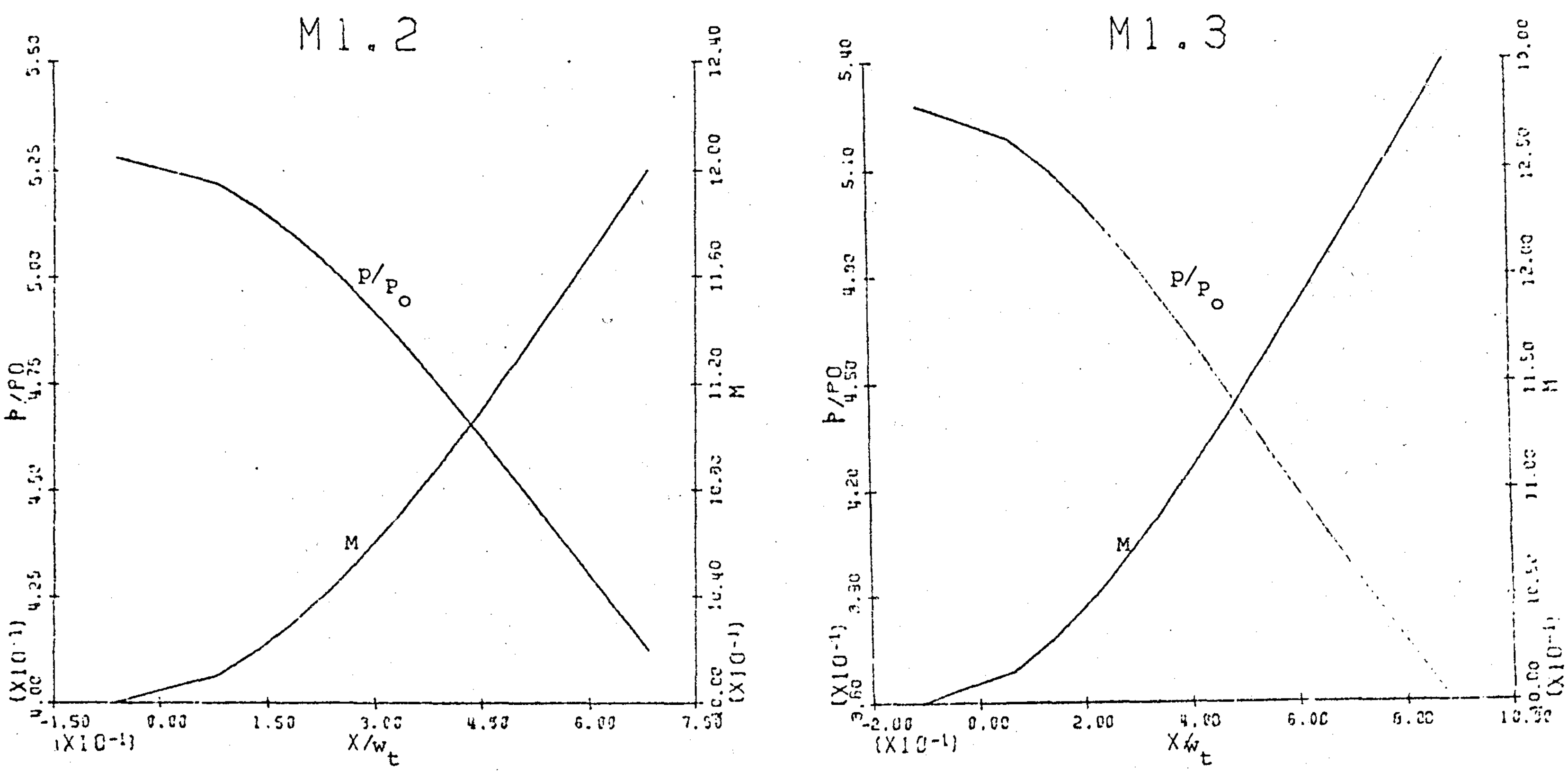


Fig. 4 Pressure Ratio (p/p_o), and Flow Mach Number (M) Profiles along the Plug Surface for an $M_e = 1.2$ and $M_e = 1.3$ Isentropic Plug-Nozzle.

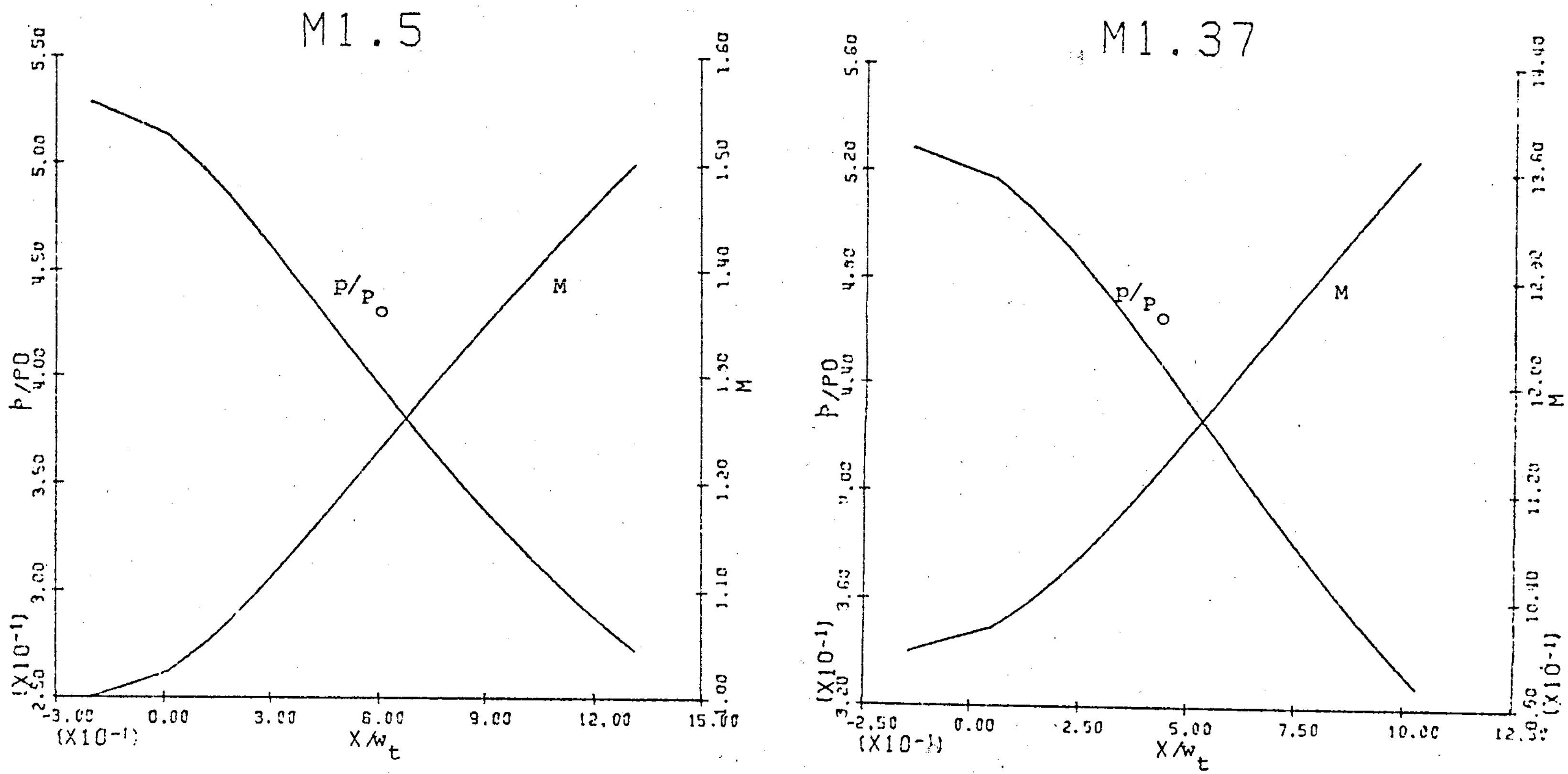


Fig. 5 Pressure Ratio (p/p_o), and Mach Number (M) Profiles along the Plug Surface for an $M_e = 1.37$ and $M_e = 1.5$ Isentropic Plug-Nozzle.

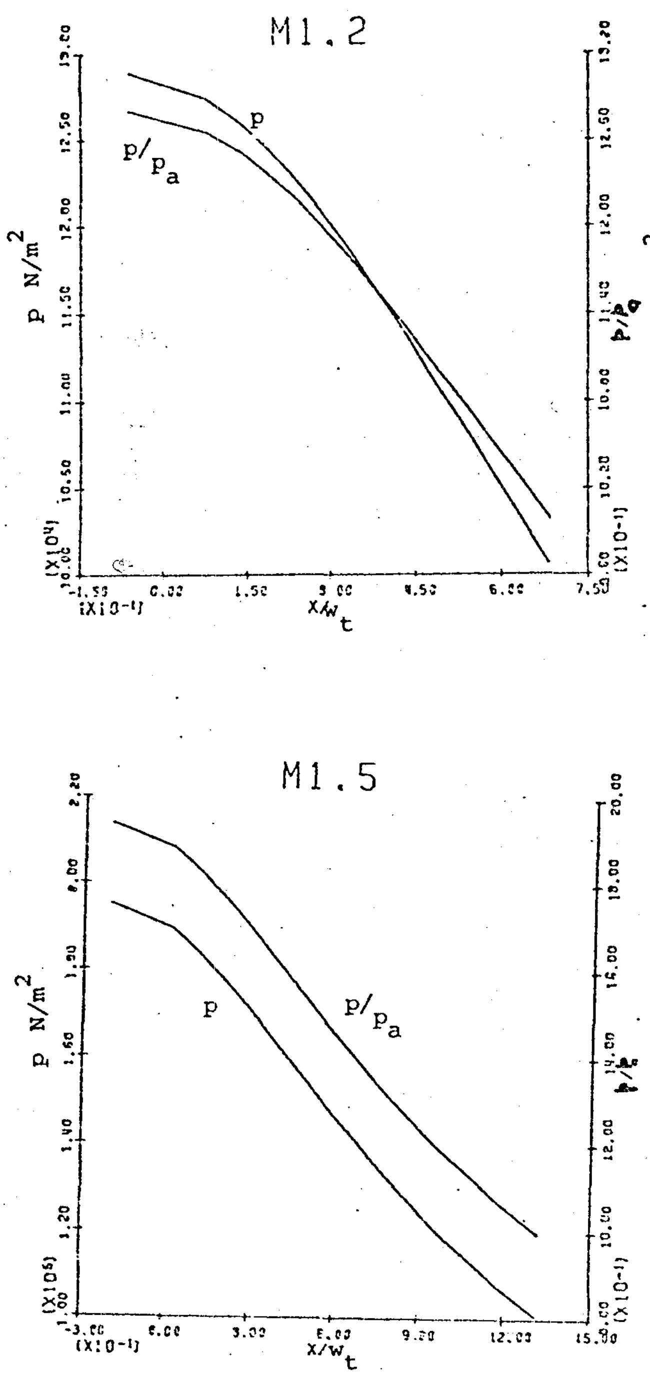


Fig. 6. Static Pressure p and Pressure Ratio p/p_a distribution on the Surface of the Plug.

Fig. 7 Variation of the Ratio of the Maximum Plug Length to the Annulus-Height at the Throat as a Function of the design Flow Mach Number or Pressure Ratios.

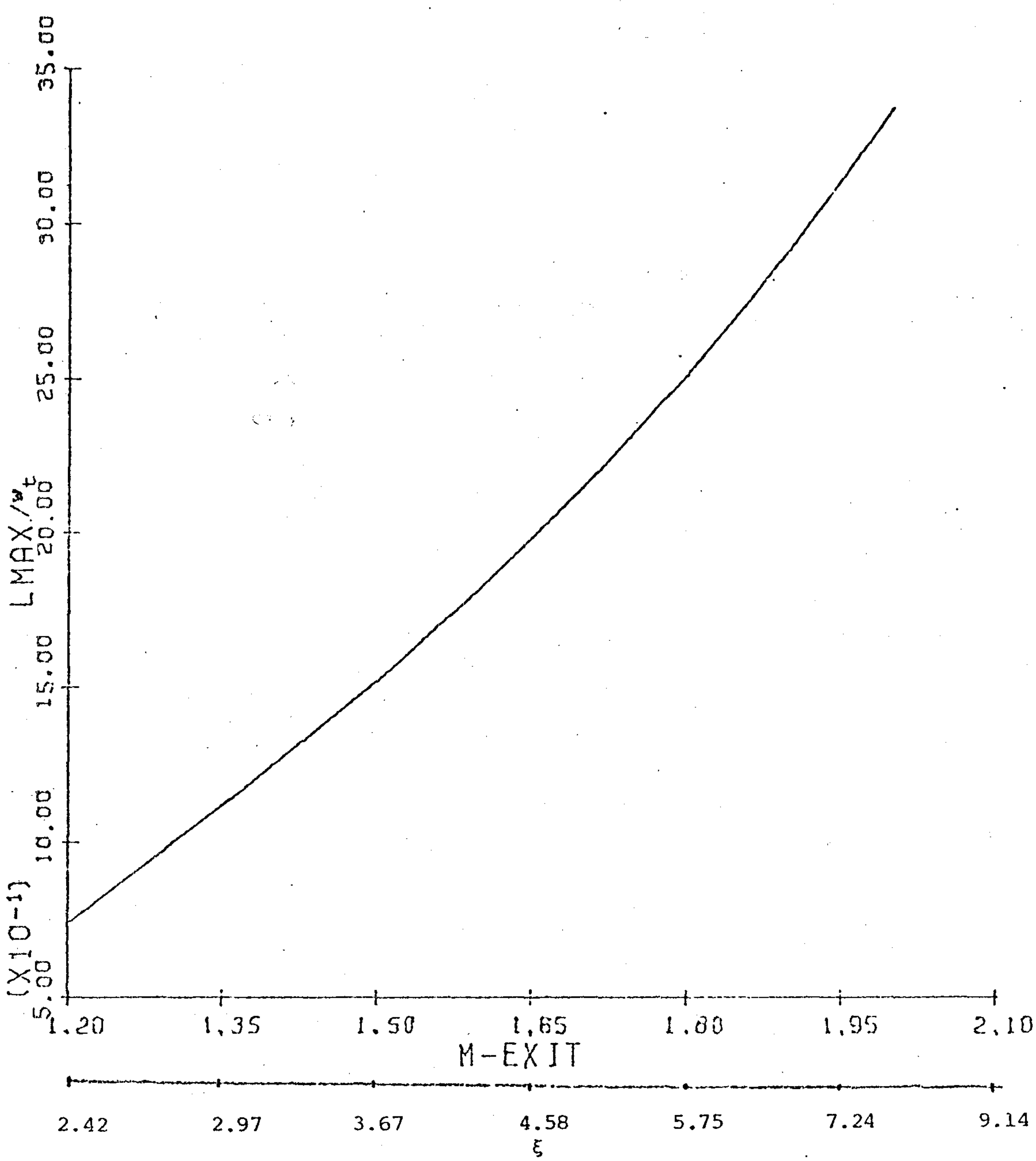


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Table 1.

NOZLE1 1.2

Non-Dimensional Flow Properties and Geometrical Parameters of Isentropic External-Expansion Plug-Nozzles at Different Design (Exit) Flow Mach Numbers (Tables 1-4).

EXIT MACH NUMBER: 1.2

EXIT ω : 3.55829°

ϕ in Tables is measured with respect to the free jet boundary.

NO	M	P/PO	T/TO	ρ/ρO	A/A*	r/w_t	ϕ	X/w_t	Y/w_t	L/LMAX
1	1.000	0.5283	0.8333	0.6339	1.0000	1.0000	93.56	-0.0621	0.9981	0.0000
2	1.010	0.5221	0.8306	0.6287	1.0001	1.0101	85.45	0.0802	1.0069	0.1708
3	1.020	0.5160	0.8278	0.6234	1.0003	1.0203	82.07	0.1408	1.0106	0.2721
4	1.030	0.5099	0.8250	0.6181	1.0007	1.0308	79.47	0.1884	1.0134	0.3360
5	1.040	0.5039	0.8222	0.6129	1.0013	1.0414	77.27	0.2296	1.0157	0.3911
6	1.050	0.4979	0.8193	0.6077	1.0020	1.0521	75.32	0.2667	1.0178	0.4409
7	1.060	0.4919	0.8165	0.6024	1.0029	1.0631	73.55	0.3010	1.0196	0.4870
8	1.070	0.4860	0.8137	0.5972	1.0039	1.0742	71.92	0.3334	1.0212	0.5303
9	1.080	0.4800	0.8108	0.5920	1.0051	1.0855	70.40	0.3642	1.0226	0.5717
10	1.090	0.4742	0.8080	0.5869	1.0064	1.0970	68.96	0.3938	1.0239	0.6114
11	1.100	0.4684	0.8052	0.5817	1.0079	1.1087	67.60	0.4225	1.0251	0.6499
12	1.110	0.4626	0.8023	0.5766	1.0095	1.1206	66.30	0.4504	1.0261	0.6873
13	1.120	0.4568	0.7994	0.5714	1.0113	1.1327	65.06	0.4777	1.0270	0.7239
14	1.130	0.4511	0.7966	0.5663	1.0132	1.1449	63.86	0.5044	1.0278	0.7598
15	1.140	0.4455	0.7937	0.5612	1.0153	1.1574	62.70	0.5308	1.0285	0.7951
16	1.150	0.4398	0.7908	0.5562	1.0175	1.1701	61.59	0.5568	1.0291	0.8300
17	1.160	0.4343	0.7879	0.5511	1.0198	1.1829	60.50	0.5825	1.0296	0.8645
18	1.170	0.4287	0.7851	0.5461	1.0222	1.1960	59.45	0.6080	1.0300	0.8987
19	1.180	0.4232	0.7822	0.5411	1.0248	1.2093	58.42	0.6333	1.0302	0.9326
20	1.190	0.4178	0.7793	0.5361	1.0276	1.2228	57.42	0.6585	1.0304	0.9664
21	1.200	0.4124	0.7764	0.5311	1.0304	1.2365	56.44	0.6835	1.0304	1.0000

Table 2.

NOZLE1 1.3

EXIT MACH NUMBER: 1.3

EXIT ω : 6.17039°

NO	M	P/PO	T/TO	ρ/ρO	A/A*	z/w_t	φ	X/w_t	Y/w_t	L/LMAX
1	1.000	0.5283	0.8333	0.6339	1.0000	1.0000	96.17	-0.1075	0.9942	0.0000
2	1.015	0.5191	0.8292	0.6260	1.0002	1.0152	86.23	0.0668	1.0130	0.1755
3	1.030	0.5099	0.8250	0.6181	1.0007	1.0308	82.08	0.1421	1.0209	0.2512
4	1.045	0.5009	0.8207	0.6103	1.0016	1.0467	78.88	0.2019	1.0271	0.3115
5	1.060	0.4919	0.8165	0.6024	1.0029	1.0631	76.16	0.2542	1.0322	0.3642
6	1.075	0.4830	0.8123	0.5946	1.0045	1.0798	73.76	0.3020	1.0368	0.4123
7	1.090	0.4742	0.8080	0.5869	1.0064	1.0970	71.58	0.3467	1.0408	0.4573
8	1.105	0.4655	0.8037	0.5791	1.0087	1.1146	69.56	0.3893	1.0444	0.5002
9	1.120	0.4568	0.7994	0.5714	1.0113	1.1327	67.67	0.4304	1.0477	0.5415
10	1.135	0.4483	0.7951	0.5638	1.0142	1.1511	65.89	0.4703	1.0507	0.5817
11	1.150	0.4398	0.7908	0.5562	1.0175	1.1701	64.20	0.5093	1.0534	0.6210
12	1.165	0.4315	0.7865	0.5486	1.0210	1.1895	62.58	0.5477	1.0558	0.6597
13	1.180	0.4232	0.7822	0.5411	1.0248	1.2093	61.03	0.5857	1.0580	0.6977
14	1.195	0.4151	0.7778	0.5336	1.0290	1.2296	59.54	0.6233	1.0599	0.7358
15	1.210	0.4070	0.7735	0.5262	1.0334	1.2505	58.10	0.6608	1.0616	0.7735
16	1.225	0.3991	0.7692	0.5188	1.0382	1.2718	56.71	0.6981	1.0630	0.8111
17	1.240	0.3912	0.7648	0.5115	1.0432	1.2936	55.35	0.7355	1.0642	0.8487
18	1.255	0.3835	0.7605	0.5043	1.0486	1.3159	54.04	0.7728	1.0651	0.8863
19	1.270	0.3759	0.7561	0.4971	1.0542	1.3388	52.76	0.8103	1.0658	0.9240
20	1.285	0.3683	0.7517	0.4900	1.0601	1.3622	51.51	0.8479	1.0662	0.9619
21	1.300	0.3609	0.7474	0.4829	1.0663	1.3862	50.29	0.8857	1.0663	1.0000

Table 3.

NOZLE1 1.37

EXIT MACH NUMBER: 1.37

EXIT ω : 8.12775°

NO	M	P/PO	T/TO	$\rho/\rho O$	A/A*	r/w_t	ϕ	X/w_t	Y/w_t	L/LMAX
1	1.000	0.5283	0.8333	0.6339	1.0000	1.0000	98.13	-0.1414	0.9900	0.0000
2	1.019	0.5169	0.8282	0.6242	1.0003	1.0188	87.08	0.0519	1.0175	0.1651
3	1.037	0.5057	0.8230	0.6145	1.0011	1.0382	82.46	0.1362	1.0292	0.2371
4	1.055	0.4946	0.8178	0.6048	1.0025	1.0581	78.90	0.2038	1.0383	0.2949
5	1.074	0.4836	0.8125	0.5951	1.0044	1.0787	75.87	0.2633	1.0461	0.3458
6	1.092	0.4727	0.8073	0.5856	1.0068	1.0999	73.19	0.3182	1.0529	0.3926
7	1.111	0.4620	0.8020	0.5760	1.0097	1.1218	70.75	0.3699	1.0590	0.4368
8	1.130	0.4514	0.7967	0.5666	1.0131	1.1443	68.49	0.4196	1.0646	0.4793
9	1.148	0.4410	0.7914	0.5572	1.0170	1.1675	66.38	0.4679	1.0697	0.5205
10	1.166	0.4306	0.7861	0.5478	1.0214	1.1914	64.38	0.5151	1.0743	0.5609
11	1.185	0.4205	0.7807	0.5386	1.0262	1.2160	62.49	0.5618	1.0785	0.6007
12	1.204	0.4105	0.7754	0.5294	1.0315	1.2414	60.68	0.6080	1.0823	0.6402
13	1.222	0.4007	0.7700	0.5203	1.0372	1.2675	58.94	0.6540	1.0857	0.6795
14	1.241	0.3910	0.7647	0.5113	1.0434	1.2943	57.27	0.6999	1.0888	0.7187
15	1.259	0.3814	0.7593	0.5024	1.0500	1.3220	55.65	0.7460	1.0914	0.7581
16	1.277	0.3721	0.7539	0.4935	1.0571	1.3505	54.08	0.7922	1.0937	0.7976
17	1.296	0.3629	0.7485	0.4848	1.0646	1.3798	52.57	0.8387	1.0956	0.8373
18	1.315	0.3538	0.7432	0.4761	1.0726	1.4099	51.09	0.8856	1.0971	0.8773
19	1.333	0.3450	0.7378	0.4676	1.0810	1.4409	49.65	0.9329	1.0981	0.9178
20	1.352	0.3363	0.7324	0.4591	1.0898	1.4728	48.25	0.9807	1.0988	0.9586
21	1.370	0.3277	0.7271	0.4508	1.0990	1.5057	46.88	1.0292	1.0990	1.0000

Table 4.

NOZLE1 1.5

EXIT MACH NUMBER: 1.5

EXIT ω : 11.9054°

NO	M	P/PO	T/TO	ρ/ρO	A/A*	r/w_t	ϕ	X/w_t	Y/w_t	L/LMAX
1	1.000	0.5283	0.8333	0.6339	1.0000	1.0000	101.91	-0.2063	0.9785	0.0000
2	1.025	0.5130	0.8264	0.6208	1.0005	1.0255	89.05	0.0170	1.0254	0.1468
3	1.050	0.4979	0.8193	0.6077	1.0020	1.0521	83.67	0.1161	1.0457	0.2119
4	1.075	0.4830	0.8123	0.5946	1.0045	1.0798	79.50	0.1969	1.0617	0.2650
5	1.100	0.4684	0.8052	0.5817	1.0079	1.1087	75.95	0.2692	1.0755	0.3125
6	1.125	0.4540	0.7980	0.5689	1.0122	1.1388	72.80	0.3367	1.0879	0.3570
7	1.150	0.4398	0.7908	0.5562	1.0175	1.1701	69.93	0.4015	1.0990	0.3995
8	1.175	0.4260	0.7836	0.5436	1.0235	1.2026	67.28	0.4646	1.1093	0.4410
9	1.200	0.4124	0.7764	0.5311	1.0304	1.2365	64.79	0.5267	1.1187	0 4818
10	1.225	0.3991	0.7692	0.5188	1.0382	1.2718	62.44	0.5884	1.1275	0.5224
11	1.250	0.3861	0.7619	0.5067	1.0468	1.3084	60.21	0.6502	1.1355	0.5630
12	1.275	0.3733	0.7546	0.4947	1.0561	1.3466	58.07	0.7122	1.1428	0.6037
13	1.300	0.3609	0.7474	0.4829	1.0663	1.3862	56.02	0.7748	1.1495	0.6449
14	1.325	0.3488	0.7401	0.4713	1.0773	1.4274	54.05	0.8381	1.1555	0.6865
15	1.350	0.3370	0.7329	0.4598	1.0890	1.4702	52.14	0.9023	1.1607	0.7287
16	1.375	0.3255	0.7256	0.4485	1.1016	1.5147	50.29	0.9677	1.1653	0.7717
17	1.400	0.3142	0.7184	0.4374	1.1149	1.5609	48.50	1.0342	1.1691	0.8154
18	1.425	0.3033	0.7112	0.4265	1.1291	1.6089	46.76	1.1021	1.1721	0.8601
19	1.450	0.2927	0.7040	0.4158	1.1440	1.6587	45.07	1.1715	1.1743	0.9057
20	1.475	0.2824	0.6968	0.4053	1.1597	1.7105	43.42	1.2424	1.1757	0.9523
21	1.500	0.2724	0.6897	0.3950	1.1762	1.7643	41.81	1.3150	1.1762	1.0000

A1 NOZLE1 1.37

Table 5. Coordinates of the Contours of Isentropic External-Expansion Plug-Nozzle for Different Ratios of the Plug Radius to Nozzle Radius (Tables 5-7; M_e = 1.37; A^* = 7.913 cm^2).

EXIT MACH NUMBER: 1.37

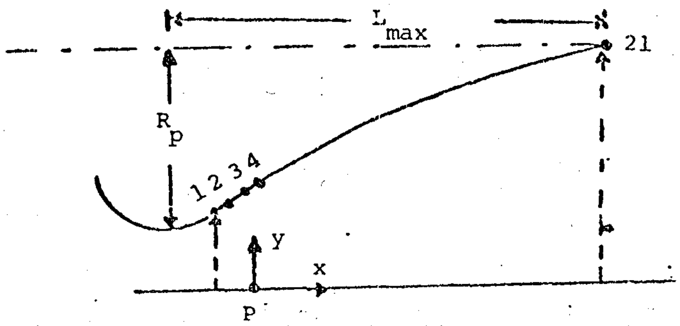
EXIT ω : 8.1278°

PLUG THROAT REGION PARAMETERS

K= 0.2
RN= 4.995 CM
RP= 0.999 CM
w_t = 3.996 CM LMAX= 4.6774 CM

NO	M	p/PO	T/TO	ρ/ρO	A/A*	r/w_t	ϕ	x/w_t	y/w_t	L/LMAX	X	Y
1	1.000	0.5283	0.8333	0.6339	1.0000	1.0000	78.13	−0.1414	0.9900	0.0000	−0.5619	3.9552
2	1.017	0.5169	0.8282	0.6242	1.0003	1.0188	87.08	0.0519	1.0175	0.1651	0.2075	4.0658
3	1.037	0.5057	0.8230	0.6145	1.0011	1.0382	82.46	0.1362	1.0292	0.2371	0.5411	4.1126
4	1.055	0.4946	0.8178	0.6048	1.0025	1.0581	78.90	0.2038	1.0383	0.2949	0.8143	4.1491
5	1.074	0.4836	0.8125	0.5951	1.0044	1.0787	75.87	0.2633	1.0461	0.3458	1.0533	4.1851
6	1.092	0.4727	0.8073	0.5856	1.0068	1.0999	73.19	0.3182	1.0529	0.3926	1.2714	4.2074
7	1.111	0.4620	0.8020	0.5760	1.0097	1.1218	70.75	0.3699	1.0590	0.4368	1.4782	4.2317
8	1.130	0.4514	0.7967	0.5666	1.0131	1.1443	68.49	0.4196	1.0646	0.4793	1.6758	4.2542
9	1.148	0.4410	0.7914	0.5572	1.0170	1.1675	66.38	0.4679	1.0697	0.5205	1.8696	4.2744
10	1.166	0.4306	0.7861	0.5478	1.0214	1.1914	64.38	0.5151	1.0743	0.5609	2.0585	4.2929
11	1.185	0.4205	0.7807	0.5386	1.0262	1.2160	62.49	0.5618	1.0785	0.6007	2.2448	4.3097
12	1.204	0.4105	0.7754	0.5294	1.0315	1.2414	60.68	0.6080	1.0823	0.6402	2.4295	4.3249
13	1.222	0.4007	0.7700	0.5203	1.0372	1.2675	58.94	0.6540	1.0857	0.6795	2.6137	[illegible]
14	1.241	0.3910	0.7647	0.5113	1.0434	1.2943	57.27	0.6999	1.0888	0.7187	2.7969	4.3507
15	1.259	0.3814	0.7593	0.5024	1.0500	1.3220	55.65	0.7460	1.0914	0.7581	2.9809	4.3613
16	1.277	0.3721	0.7539	0.4935	1.0571	1.3505	54.08	0.7922	1.0937	0.7976	3.1656	4.3704
17	1.296	0.3629	0.7485	0.4848	1.0646	1.3798	52.57	0.8387	1.0956	0.8373	3.3514	4.3779
18	1.315	0.3538	0.7432	0.4761	1.0726	1.4099	51.09	0.8856	1.0971	0.8773	3.5308	4.3839
19	1.333	0.3450	0.7378	0.4676	1.0810	1.4409	49.65	0.9329	1.0981	0.9178	3.7279	4.3882
20	1.352	0.3363	0.7324	0.4591	1.0898	1.4728	48.25	0.9807	1.0988	0.9586	3.9191	4.3903
21	1.370	0.3277	0.7271	0.4508	1.0990	1.5057	46.88	1.0292	1.0990	1.0000	4.1125	4.3917

Table 5a.



EXIT MACH NUMBER: 1.37

EXIT ω : 8.1278°

PLUG_THROAT_DESIGN_PARAMETERS

K= 0.2
RN= 4.995 CM
RF= 0.999 CM
W_t= 3.996 CM

Throat area = 7.913 cm^2
Equivalent to that of a 3.175 cm diameter round nozzle.

LMAX= 4.6774 CM

NO	M	X	Y
1	1.000	-0.5649	3.9559
2	1.019	0.2075	4.0658
3	1.037	0.5441	4.1126
4	1.055	0.8143	4.1491
5	1.074	1.0523	4.1801
6	1.092	1.2714	4.2074
7	1.111	1.4782	4.2319
8	1.130	1.6768	4.2542
9	1.148	1.8696	4.2744
10	1.166	2.0585	4.2929
11	1.185	2.2448	4.3097
12	1.204	2.4295	4.3249
13	1.222	2.6133	4.3386
14	1.241	2.7969	4.3507
15	1.259	2.9809	4.3613
16	1.277	3.1656	4.3704
17	1.296	3.3514	4.3779
18	1.315	3.5388	4.3839
19	1.333	3.7279	4.3882
20	1.352	3.9191	4.3908
21	1.370	4.1125	4.3917

.5 6.39

19 3.159 3.159 NOZLE1 1.37 Table 6.

EXIT MACH NUMBER: 1.37

EXIT ω : 8.1278°

PLUG_INLET_REGION_PARAMETERS

K= 0.5

RN= 6.319 CM

RP= 3.159 CM

w_t= 3.159 CM LMAX= 3.6977 CM

NO	M	P/PO	T/TO	ρ/ρ_O	A/A*	r/w_t	ϕ	x/w_t	y/w_t	L/LMAX	X	Y
1	1.000	0.5283	0.8333	0.6339	1.0000	1.0000	98.13	‾0.1414	0.9900	0.0000	‾0.4443	3.1[illegible]
2	1.019	0.5167	0.8282	0.6242	1.0003	1.0108	87.08	0.0519	1.0175	0.1651	0.1649	3.2142
3	1.037	0.5057	0.8230	0.6145	1.0011	1.0302	82.46	0.1362	1.0292	0.2371	0.4301	3.2512
4	1.055	0.4946	0.8178	0.6048	1.0025	1.0581	78.90	0.2038	1.0383	0.2949	0.6157	3.[illegible]
5	1.074	0.4836	0.8125	0.5951	1.0044	1.0787	75.07	0.2653	1.0461	0.3458	[illegible]	[illegible]
6	1.092	0.4727	0.8073	0.5856	1.0068	1.0999	73.19	0.3182	1.0529	0.3926	1.0551	[illegible]
7	1.111	0.4620	0.8020	0.5760	1.0097	1.1218	70.75	0.3699	1.0590	0.4360	[illegible]	[illegible]
8	1.130	0.4514	0.7967	0.5666	1.0131	1.1443	68.49	0.4196	1.0646	0.4793	1.3256	3.3431
9	1.148	0.4410	0.7914	0.5572	1.0170	1.1675	66.38	0.4679	1.0697	0.5205	1.4780	3.3791
10	1.166	0.4306	0.7861	0.5478	1.0214	1.1914	64.38	0.5151	1.0743	0.5609	1.6273	3.3937
11	1.185	0.4205	0.7807	0.5386	1.0262	1.2160	62.49	0.5618	1.0785	0.6007	1.7746	3.4070
12	1.204	0.4105	0.7754	0.5294	1.0315	1.2414	60.68	0.6080	1.0823	0.6402	1.9206	3.4190
13	1.222	0.4007	0.7700	0.5203	1.0372	1.2675	58.94	0.6540	1.0857	0.6795	2.0659	3.4298
14	1.241	0.3910	0.7647	0.5113	1.0434	1.2943	57.27	0.6999	1.0888	0.7187	2.2111	3.4394
15	1.259	0.3814	0.7593	0.5024	1.0500	1.3220	55.65	0.7460	1.0914	0.7581	2.3565	3.4478
16	1.277	0.3721	0.7539	0.4935	1.0571	1.3505	54.08	0.7922	1.0937	0.7976	2.5025	3.4550
17	1.296	0.3629	0.7485	0.4848	1.0646	1.3798	52.57	0.8387	1.0956	0.8373	2.6495	3.4609
18	1.315	0.3538	0.7432	0.4761	1.0726	1.4099	51.09	0.8856	1.0971	0.8773	2.7976	3.4656
19	1.333	0.3450	0.7378	0.4676	1.0810	1.4409	49.65	0.9329	1.0981	0.9178	2.9471	[illegible]
20	1.352	0.3363	0.7324	0.4591	1.0898	1.4728	48.25	0.9807	1.0988	0.9586	3.0982	[illegible]
21	1.370	0.3277	0.7271	0.4508	1.0990	1.5057	46.88	1.0292	1.0990	1.0000	3.2511	3.4712

.9 14.129 12.716 1.413 NOZLE1 1.37

Table 7.

EXIT MACH NUMBER: 1.37

EXIT ω : 8.1278°

PLUG_THROAT_REGION_PARAMETERS
ε= 0.9
RE= 14.129 CM
RI= 12.716 CM
w_t= 1.413 CM LMAX= 1.654 CM

NO	M	P/PO	T/TO	ρ/ρO	A/A*	r/w_t	ϕ	X/w_t	Y/w_t	L/LMAX	X	Y
1	1.000	0.5283	0.8333	0.6339	1.0000	1.0000	90.13	-0.1414	0.9900	0.0000	-0.1990	1.3920
2	1.019	0.5149	0.8282	0.6242	1.0003	1.0188	87.08	0.0519	1.0175	0.1651	[illegible]	[illegible]
3	1.037	0.5057	0.8230	0.6145	1.0011	1.0382	82.46	0.1362	1.0292	0.2371	[illegible]	[illegible]
4	1.055	0.4946	0.8178	0.6048	1.0025	1.0581	78.90	0.2038	1.0383	0.2949	0.2877	[illegible]
5	1.074	0.4836	0.8125	0.5951	1.0044	1.0787	75.87	0.2733	1.0461	0.3408	[illegible]	[illegible]
6	1.092	0.4727	0.8073	0.5856	1.0068	1.0999	73.19	0.3182	1.0529	0.3726	[illegible]	[illegible]
7	1.111	0.4620	0.8020	0.5760	1.0097	1.1218	70.75	0.3677	1.0590	[illegible]	[illegible]	[illegible]
8	1.130	0.4514	0.7967	0.5666	1.0131	1.1443	68.49	0.4176	1.0646	[illegible]	0.5729	[illegible]
9	1.148	0.4410	0.7914	0.5572	1.0170	1.1675	66.38	0.4677	1.0697	[illegible]	[illegible]	[illegible]
10	1.166	0.4306	0.7861	0.5478	1.0214	1.1914	64.38	0.5151	1.0743	[illegible]	[illegible]	1.5160
11	1.185	0.4205	0.7807	0.5386	1.0262	1.2160	62.49	0.5618	1.0785	[illegible]	[illegible]	1.5239
12	1.204	0.4105	0.7754	0.5294	1.0315	1.2414	60.68	0.6080	1.0820	[illegible]	0.8821	1.5273
13	1.222	0.4007	0.7700	0.5203	1.0372	1.2675	58.74	0.6540	1.0857	0.6795	[illegible]	[illegible]
14	1.241	0.3910	0.7647	0.5113	1.0434	1.2943	57.27	0.6999	1.0888	0.7187	[illegible]	[illegible]
15	1.259	0.3814	0.7593	0.5024	1.0500	1.3220	55.65	0.7460	1.0915	0.7581	1.0510	[illegible]
16	1.277	0.3721	0.7539	0.4935	1.0571	1.3505	54.08	0.7922	1.0937	0.7976	1.1174	[illegible]
17	1.296	0.3629	0.7485	0.4848	1.0646	1.3798	52.57	0.8387	1.0956	0.8373	1.1851	1.5431
18	1.315	0.3538	0.7432	0.4761	1.0726	1.4099	51.09	0.8856	1.0971	0.8773	1.2513	[illegible]
19	1.333	0.3450	0.7378	0.4676	1.0810	1.4409	49.65	0.9329	1.0981	0.9178	1.3182	1.5517
20	1.352	0.3363	0.7324	0.4591	1.0898	1.4728	48.25	0.9807	1.0988	0.9586	1.3853	1.5526
21	1.370	0.3277	0.7271	0.4508	1.0990	1.5057	46.88	1.0292	1.0990	1.0000	1.4542	1.5529

.2 9.791 1.958 7.833 NOZLE1 1.37

Table 8. Coordinates of the contours of Isentropic External-Expansion Plug-Nozzle for Different Ratios of the Plug Radius to Nozzle Radius (Tables 8 to 10; M_e = 1.37; A^* = 15.518 cm^2.

EXIT MACH NUMBER: 1.37

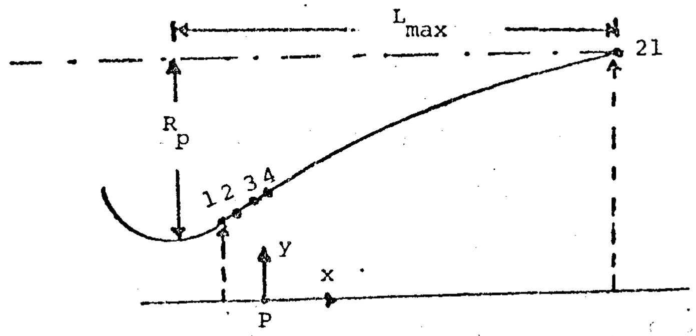
EXIT ω : 8.1278°

PLUG THROAT REGION PARAMETERS

K= 0.2
RN= 9.791 CM
RP= 1.958 CM
W_t= 7.833 CM   LMAX= 9.1688 CM

NO	M	p/p_0	T/T_0	ρ/ρ_0	A/A^*	r/w_t	ϕ	X/w_t	Y/w_t	L/LMAX	X	Y
1	1.000	0.5283	0.8333	0.6339	1.0000	1.0000	98.13	−0.1414	0.9900	0.0000	−1.1074	7.7573
2	1.019	0.5169	0.8282	0.6242	1.0003	1.0188	87.08	0.0519	1.0175	0.1651	0.4057	[illegible]
3	1.037	0.5057	0.8230	0.6145	1.0011	1.0382	82.46	0.1362	1.0292	0.2371	1.0666	[illegible]
4	1.055	0.4946	0.8178	0.6048	1.0025	1.0581	78.[illegible]0	0.2038	1.0383	0.2949	[illegible]	[illegible]
5	1.074	0.4836	0.8125	0.5951	1.0044	1.0787	75.87	0.2653	1.0461	0.3458	[illegible]	[illegible]
6	1.093	0.4727	0.8073	0.5856	1.0068	1.0999	73.19	0.3182	1.0529	0.3926	[illegible]	[illegible]
7	1.111	0.4620	0.8020	0.5760	1.0097	1.1218	70.75	0.3699	1.0590	0.4368	[illegible]	[illegible]
8	1.130	0.4514	0.7967	0.5666	1.0131	1.1443	68.49	0.4126	1.0646	0.4793	[illegible]	[illegible]
9	1.148	0.4410	0.7914	0.5572	1.0170	1.1675	66.38	0.4679	1.0697	0.5205	3.6618	8.3708
10	1.166	0.4306	0.7861	0.5478	1.0214	1.1914	64.38	0.5151	1.0743	0.5609	[illegible]	[illegible]
11	1.185	0.4205	0.7807	0.5386	1.0262	1.2160	62.49	0.5618	1.0785	0.6007	[illegible]	[illegible]
12	1.204	0.4105	0.7754	0.5294	1.0315	1.2414	60.68	0.6080	1.0823	0.6402	[illegible]	[illegible]
13	1.222	0.4007	0.7700	0.5203	1.0372	1.2675	58.94	0.6540	1.0857	0.6795	5.1226	[illegible]
14	1.241	0.3910	0.7647	0.5113	1.0434	1.2943	57.27	0.6999	1.0888	0.7187	[illegible]	[illegible]
15	1.259	0.3814	0.7593	0.5024	1.0500	1.3220	55.65	0.7460	1.0914	0.7581	5.8431	8.5491
16	1.277	0.3721	0.7539	0.4935	1.0571	1.3505	54.08	0.7922	1.0937	0.7976	6.2052	[illegible]
17	1.296	0.3629	0.7485	0.4848	1.0646	1.3798	52.57	0.8387	1.0956	0.8373	[illegible]	8.5617
18	1.315	0.3538	0.7432	0.4761	1.0726	1.4099	51.09	0.8856	1.0971	0.8773	[illegible]	[illegible]
19	1.333	0.3450	0.7378	0.4676	1.0810	1.4409	49.65	0.9329	1.0981	0.9178	[illegible]	[illegible]
20	1.352	0.3363	0.7324	0.4591	1.0898	1.4728	48.25	0.9807	1.0988	0.9586	[illegible]	[illegible]
21	1.370	0.3277	0.7271	0.4508	1.0990	1.5057	46.88	1.0292	1.0990	1.0000	8.0613	8.6036

Table 8a.



EXIT MACH NUMBER: 1.37

EXIT ω : 8.1278°

PLUG_THROAT_REGION_PARAMETERS

K= 0.2

RN= 9.791 CM

RF= 1.958 CM

W_t= 7.833 CM

Throat area = 15.518 cm^2

Equivalent to that of a 4.445 cm diameter round nozzle

LMAX= 9.1688 CM

NO	M	X	Y
1	1.000	-1.1074	7.7543
2	1.019	0.4067	7.9698
3	1.037	1.0666	8.0617
4	1.055	1.5961	8.1332
5	1.074	2.0628	8.1939
6	1.092	2.4922	8.2475
7	1.111	2.8977	8.2955
8	1.130	3.2869	8.3391
9	1.148	3.6648	8.3788
10	1.166	4.0351	8.4150
11	1.185	4.4003	8.4479
12	1.204	4.7623	8.4777
13	1.222	5.1226	8.5045
14	1.241	5.4825	8.5283
15	1.259	5.8431	8.5491
16	1.277	6.2052	8.5669
17	1.296	6.5695	8.5817
18	1.315	6.9368	8.5933
19	1.333	7.3075	8.6017
20	1.352	7.6822	8.6069
21	1.370	8.0613	8.6086

.5 12.385 6.192 6.192 NOZLE1 1.37

Table 9.

EXIT MACH NUMBER: 1.37

EXIT ω : 8.1278°

PLUG THROAT REGION PARAMETERS

K= 0.5

RN= 12.385 CM

RT= 6.192 CM

w_t = 6.192 CM LMAX= 7.2479 CM

NO	M	P/PO	T/TO	ρ/ρO	A/A*	r/w_t	φ	X/w_t	Y/w_t	L/LMAX	X	Y
1	1.000	0.5283	0.8333	0.6339	1.0000	1.0000	98.13	‾0.1414	0.9900	0.0000	‾0.8751	6.1295
2	1.019	0.5167	0.8282	0.6242	1.0003	1.0188	87.08	0.0519	1.0175	0.1651	0.3213	6.3001
3	1.037	0.5057	0.8230	0.6145	1.0011	1.0382	82.46	0.1362	1.0292	0.2371	0.8151	6.3720
4	1.055	0.4946	0.8178	0.6048	1.0025	1.0581	78.90	0.2038	1.0383	0.2949	1.2618	6.4272
5	1.074	0.4836	0.8125	0.5951	1.0044	1.0787	75.87	0.2633	1.0461	0.3458	1.6306	6.47[illegible]
6	1.092	0.4727	0.8073	0.5856	1.0068	1.0999	73.19	0.3182	1.0529	0.3926	1.9701	6.5196
7	1.111	0.4620	0.8020	0.5760	1.0097	1.1218	70.75	0.3699	1.0590	0.4368	2.2906	6.5576
8	1.130	0.4514	0.7967	0.5666	1.0131	1.1443	68.49	0.4196	1.0646	0.4793	2.5983	6.5921
9	1.148	0.4410	0.7914	0.5572	1.0170	1.1675	66.38	0.4679	1.0697	0.5205	2.8971	6.6234
10	1.166	0.4306	0.7861	0.5478	1.0214	1.1914	64.38	0.5151	1.0743	0.5607	3.1898	6.6520
11	1.185	0.4205	0.7807	0.5386	1.0262	1.2160	62.49	0.5613	1.0785	0.6007	3.4754	6.6781
12	1.204	0.4105	0.7754	0.5294	1.0315	1.2414	60.38	0.6080	1.0823	0.6402	3.7646	6.7017
13	1.222	0.4007	0.7700	0.5203	1.0372	1.2675	58.94	0.6540	1.0857	0.6795	4.0494	6.7220
14	1.241	0.3910	0.7647	0.5113	1.0434	1.2945	57.27	0.6999	1.0888	0.7187	4.3340	6.7416
15	1.259	0.3811	0.7593	0.5024	1.0500	1.3220	55.65	0.7460	1.0914	0.7581	4.6190	6.7581
16	1.277	0.3721	0.7539	0.4935	1.0571	1.3505	54.08	0.7922	1.0937	0.7976	4.9052	6.7722
17	1.296	0.3629	0.7485	0.4848	1.0646	1.3798	52.57	0.8387	1.0956	0.8373	5.1932	6.7836
18	1.315	0.3538	0.7432	0.4761	1.0726	1.4099	51.09	0.8856	1.0971	0.8773	5.4835	[illegible]
19	1.333	0.3456	0.7378	0.4676	1.0810	1.4409	49.65	0.9329	1.0981	0.9178	5.7766	[illegible]
20	1.352	0.3363	0.7324	0.4591	1.0898	1.4728	48.25	0.9807	1.0988	0.9586	6.0728	6.8047
21	1.370	0.3277	0.7271	0.4508	1.0990	1.5057	46.88	1.0292	1.0990	1.0000	6.3725	6.8051

.9 27.693 24.924 2.769 NOZLE1 1.37 Table 10.

EXIT MACH NUMBER: 1.37

EXIT ω : 8.1278°

PLUG THROAT REGION PARAMETERS

K= 0.9

RU= 27.693 CM

RL= 24.924 CM

W_t= 2.769 CM LMAX= 3.2412 CM

NO	M	P/PO	T/TO	ρ/ρO	A/A*	r/w_t	ϕ	X/w_t	Y/w_t	L/LMAX	X	Y
1	1.000	0.5283	0.8333	0.6339	1.0000	1.0000	98.13	-0.1414	0.9900	0.0000	[illegible]	[illegible]
2	1.019	0.5167	0.8282	0.6242	1.0003	1.0188	87.08	0.0519	1.0175	0.1651	[illegible]	[illegible]
3	1.037	0.5057	0.8230	0.6145	1.0011	1.0382	82.46	0.1362	1.0292	0.2371	[illegible]	[illegible]
4	1.055	0.4946	0.8178	0.6048	1.0025	1.0581	78.90	0.2038	1.0383	0.2949	[illegible]	[illegible]
5	1.074	0.4836	0.8125	0.5951	1.0044	1.0787	75.87	0.2633	1.0461	0.3458	0.7292	[illegible]
6	1.092	0.4727	0.8073	0.5856	1.0068	1.0999	73.19	0.3182	1.0529	0.3926	0.8810	[illegible]
7	1.111	0.4620	0.8020	0.5760	1.0097	1.1218	70.75	0.3699	1.0590	0.4368	1.0243	[illegible]
8	1.130	0.4514	0.7967	0.5666	1.0131	1.1443	68.49	0.4196	1.0646	0.4793	[illegible]	[illegible]
9	1.148	0.4410	0.7914	0.5572	1.0170	1.1675	66.38	0.4679	1.0697	0.5205	[illegible]	[illegible]
10	1.166	0.4306	0.7861	0.5478	1.0214	1.1914	64.38	0.5151	1.0743	0.5609	[illegible]	[illegible]
11	1.185	[illegible]	0.7807	0.5386	1.0262	1.2160	62.49	0.5618	1.0785	0.6007	[illegible]	[illegible]
12	1.204	0.4105	0.7754	0.5294	1.0315	1.2414	60.68	0.6080	1.0823	0.6402	1.6835	2.9969
13	1.222	0.4007	0.7700	0.5203	1.0372	1.2675	58.94	0.6540	1.0857	0.6795	1.8109	3.0064
14	1.241	0.3910	0.7647	0.5113	1.0434	1.2943	57.27	0.6999	1.0888	0.7187	1.9351	3.0148
15	1.259	0.3814	0.7593	0.5024	1.0500	1.3220	55.65	0.7460	1.0914	0.7581	2.0606	3.0222
16	1.277	0.3721	0.7539	0.4935	1.0571	1.3505	54.08	0.7922	1.0937	0.7976	[illegible]	[illegible]
17	1.296	0.3629	0.7485	0.4848	1.0646	1.3798	52.57	0.8387	1.0956	0.8373	2.3224	3.0337
18	1.315	0.3538	0.7432	0.4761	1.0726	1.4099	51.09	0.8856	1.0971	0.8773	2.4522	3.0375
19	1.333	0.3450	0.7378	0.4676	1.0810	1.4409	49.65	0.9329	1.0981	0.9178	2.5832	3.0407
20	1.352	0.3363	0.7324	0.4591	1.0898	1.4728	48.25	0.9807	1.0988	0.9586	2.7157	3.0426
21	1.370	0.3277	0.7271	0.4508	1.0990	1.5057	46.88	1.0292	1.0990	1.0000	2.8497	[illegible]

.2 4.995 .999 3.996 NOZLE1 1.5

Table 11. Geometrical Parameters of Plug-Nozzles for Sêlected Nozzle Throat Areas and Ratio of Plug to Nozzle Radii (Tables 11-13; $M_e = 1.5$ $A^* = 7.913$ cm^2)

EXIT MACH NUMBER: 1.5

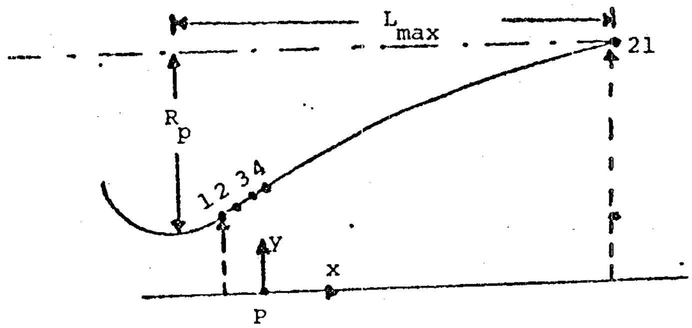
EXIT ω : 11.905°

PLUG_THROAT_REGION_PARAMETERS

K= 0.2
RN= 4.995 CM
RP= 0.999 CM
w_t = 3.996 CM LMAX= 6.0791 CM

NO	M	P/PO	T/TO	ρ/ρO	A/A*	r/w_t	φ	x/w_t	y/w_t	L/LMAX	X	Y
1	1.000	0.5283	0.8333	0.6339	1.0000	1.0000	101.91	-0.2043	0.9785	0.0000	-0.8243	3.9100
2	1.025	0.5130	0.8264	0.6208	1.0005	1.0255	99.05	0.0170	1.0254	0.1468	0.0680	4.0974
3	1.050	0.4979	0.8193	0.6077	1.0020	1.0521	83.67	0.1161	1.0457	0.2119	0.4639	4.1784
4	1.075	0.4830	0.8123	0.5946	1.0045	1.0798	79.50	0.1269	1.0617	0.2650	0.7[illegible]7	4.2427
5	1.100	0.4684	0.8052	0.5817	1.0079	1.1007	75.95	0.2492	1.0755	0.3126	1.0764	4.2979
6	1.125	0.4540	0.7980	0.5689	1.0122	1.1388	72.80	0.3347	1.0829	0.3570	1.3456	4.3471
7	1.150	0.4372	0.7908	0.5562	1.0175	1.1701	69.93	0.4015	1.0990	0.3995	1.6043	4.3917
8	1.175	0.4260	0.7836	0.5436	1.0235	1.2026	67.29	0.4646	1.1093	0.4410	1.8564	4.4327
9	1.200	0.4124	0.7764	0.5311	1.0304	1.2365	64.79	0.5267	1.1187	0.4818	2.1047	4.4705
10	1.225	0.3991	0.7692	0.5188	1.0382	1.2718	62.44	0.5884	1.1275	0.5224	2.3513	4.5057
11	1.250	0.3861	0.7619	0.5067	1.0468	1.3084	60.21	0.6502	1.1355	0.5630	2.5980	4.5374
12	1.275	0.3733	0.7546	0.4947	1.0561	1.3466	58.07	0.7122	1.1428	0.6037	2.8459	4.5657
13	1.300	0.3609	0.7474	0.4829	1.0663	1.3862	56.02	0.7748	1.1495	0.6449	3.0959	4.5923
14	1.325	0.3488	0.7401	0.4713	1.0773	1.4274	54.05	0.8381	1.1555	0.6865	3.3490	4.6172
15	1.350	0.3370	0.7329	0.4598	1.0890	1.4702	52.14	0.9023	1.1607	0.7287	3.6057	4.6383
16	1.375	0.3255	0.7256	0.4485	1.1016	1.5147	50.29	0.9677	1.1653	0.7717	3.8668	4.6545
17	1.400	0.3142	0.7184	0.4374	1.1149	1.5609	48.50	1.0342	1.1691	0.8154	4.1323	4.6717
18	1.425	0.3033	0.7112	0.4265	1.1291	1.6089	46.76	1.1021	1.1721	0.8601	4.4041	4.6[illegible]
19	1.450	0.2927	0.7040	0.4158	1.1440	1.6587	45.07	1.1715	1.1743	0.9057	4.6812	4.[illegible]
20	1.475	0.2824	0.6968	0.4053	1.1597	1.7105	43.42	1.2424	1.1757	0.9523	4.9646	4.6981
21	1.500	0.2724	0.6897	0.3950	1.1762	1.7643	41.81	1.3150	1.1762	1.0000	5.2547	4.7000

Table 11a.



EXIT MACH NUMBER: 1.5

EXIT ω : 11.905°

PLUG THROAT REGION PARAMETERS

K= 0.2

RN= 4.995 CM

RP= 0.999 CM

w_t = 3.996 CM

Throat area = 7.913 cm^2
Equivalent to that of a 3.175 diameter round nozzle.

LMAX= 6.0791 CM

NO	M	X	Y
1	1.000	⁻0.8243	3.9100
2	1.025	0.0680	4.0974
3	1.050	0.4639	4.1786
4	1.075	0.7867	4.2427
5	1.100	1.0756	4.2979
6	1.125	1.3456	4.3471
7	1.150	1.6043	4.3917
8	1.175	1.8564	4.4327
9	1.200	2.1047	4.4705
10	1.225	2.3513	4.5053
11	1.250	2.5980	4.5374
12	1.275	2.8459	4.5667
13	1.300	3.0959	4.5933
14	1.325	3.3490	4.6172
15	1.350	3.6057	4.6383
16	1.375	3.8668	4.6565
17	1.400	4.1328	4.6717
18	1.425	4.4041	4.6838
19	1.450	4.6812	4.6927
20	1.475	4.9646	4.6981
21	1.500	5.2547	4.7000

ORIGINAL PAGE IS
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.5 6.319 3.159 3.159 NOZLE1 1.5 Table 12.

EXIT MACH NUMBER: 1.5

EXIT ω : 11.905°

PLUG THROAT REGION PARAMETERS

K= 0.5

RW= 6.319 CM

RP= 3.159 CM

w_t = 3.159 CM LMAX= 4.8057 CM

NO	M	P/PO	T/TO	ρ/ρO	A/A*	r/w_t	φ	X/w_t	Y/w_t	L/LMAX	X	Y
1	1.000	0.5283	0.8333	0.6339	1.0000	1.0000	101.91	-0.2063	0.9735	0.0000	-0.6517	3.0711
2	1.025	0.5130	0.8264	0.6208	1.0005	1.0255	89.05	0.0170	1.0254	0.1468	0.0537	3.2392
3	1.050	0.4979	0.8193	0.6077	1.0020	1.0521	83.67	0.1161	1.0457	0.2119	0.3667	3.3034
4	1.075	0.4830	0.8123	0.5946	1.0045	1.0798	79.50	0.1769	1.0617	0.2630	0.4226	3.3541
5	1.100	0.4684	0.8052	0.5817	1.0079	1.1087	75.95	0.2692	1.0755	0.3125	0.8503	3.397[illegible]
6	1.125	0.4540	0.7980	0.5689	1.0122	1.1388	72.80	0.3367	1.0879	0.3570	1.0633	3.43[illegible]
7	1.150	0.4398	0.7908	0.5562	1.0175	1.1701	69.93	0.4015	1.0990	0.3995	1.[illegible]	[illegible]
8	1.175	0.4260	0.7836	0.5436	1.0235	1.2026	67.28	0.4646	1.1073	0.4410	1.4675	3.5043
9	1.200	0.4124	0.7764	0.5311	1.0304	1.2365	64.79	0.5267	1.1187	0.4818	1.6638	3.5341
10	1.225	0.3991	0.7692	0.5186	1.0382	1.2718	62.44	0.5884	1.1275	0.5224	1.8588	3.5617
11	1.250	0.3861	0.7619	0.5067	1.0468	1.3084	60.21	0.6502	1.1355	0.5630	2.0538	3.5870
12	1.275	0.3733	0.7546	0.4947	1.0561	1.3466	58.07	0.7122	1.1428	0.6077	2.2498	3.6102
13	1.300	0.3609	0.7474	0.4829	1.0663	1.3862	56.02	0.7748	1.1495	0.6442	2.4474	3.6312
14	1.325	0.3488	0.7401	0.4713	1.0773	1.4274	54.05	0.8381	1.1555	0.6865	2.6475	3.6501
15	1.350	0.3370	0.7329	0.4598	1.0890	1.4702	52.14	0.9023	1.1607	0.7287	2.8505	3.6637
16	1.375	0.3255	0.7256	0.4485	1.1016	1.5147	50.29	0.9677	1.1653	0.7717	3.0569	3.6811
17	1.400	0.3142	0.7184	0.4374	1.1149	1.5609	48.50	1.0342	1.1691	0.8154	3.2671	3.6932
18	1.425	0.3033	0.7112	0.4265	1.1291	1.6089	46.76	1.1021	1.1721	0.8601	3.4816	3.7027
19	1.450	0.2927	0.7040	0.4158	1.1440	1.6587	45.07	1.1715	1.1743	0.9057	3.7007	3.7097
20	1.475	0.2824	0.6968	0.4053	1.1597	1.7105	43.42	1.2424	1.1757	0.9523	3.9248	3.7140
21	1.500	0.2774	0.6897	0.3950	1.1762	1.7643	41.81	1.3150	1.1762	1.0000	4.1541	3.7155

.9 14.129 12.716 1.413 NOZLE1 1.5 Table 13.

EXIT MACH NUMBER: 1.5

EXIT ω : 11.905°

PLUG THROAT REGION PARAMETERS

K= 0.9
RU= 14.129 CM
RF= 12.716 CM
w_t= 1.413 CM LMAX= 2.1494 CM

NO	M	P/PO	T/TO	ρ/ρO	A/A*	r/w_t	φ	x/w_t	y/w_t	L/LMAX	X	Y
1	1.000	0.5283	0.8333	0.6339	1.0000	1.0000	101.91	−0.2063	0.9785	0.0000	−0.2215	1.3026
2	1.025	0.5130	0.8264	0.6208	1.0005	1.0255	89.05	0.0170	1.0254	0.1468	0.0240	1.4489
3	1.050	0.4979	0.8193	0.6077	1.0020	1.0521	83.67	0.1161	1.0457	0.2119	0.1640	1.4776
4	1.075	0.4830	0.8123	0.5946	1.0045	1.0798	79.50	0.1949	1.0617	0.2650	[illegible]	[illegible]
5	1.100	0.4684	0.8052	0.5817	1.0079	1.1087	75.95	0.2692	1.0755	[illegible]	[illegible]	[illegible]
6	1.125	0.4540	0.7980	0.5689	1.0122	1.1388	72.80	0.3347	1.0879	0.3570	[illegible]	[illegible]
7	1.150	0.4398	0.7908	0.5572	1.0175	1.1701	69.93	0.4015	1.0990	0.3995	0.5673	[illegible]
8	1.175	0.4260	0.7836	0.5436	1.0235	1.2026	67.28	0.4646	1.1093	0.4410	0.6564	1.5674
9	1.200	0.4124	0.7764	0.5311	1.0304	1.2365	64.79	0.5267	1.1187	0.4818	0.7412	1.5809
10	1.225	0.3991	0.7692	0.5188	1.0382	1.2718	62.44	0.5884	1.1275	0.5224	0.8314	1.5931
11	1.250	0.3861	0.7619	0.5067	1.0468	1.3084	60.21	0.6502	1.1355	0.5630	0.9187	1.6044
12	1.275	0.3733	0.7546	0.4947	1.0561	1.3466	58.07	0.7122	1.1428	0.6037	1.0063	1.6148
13	1.300	0.3607	0.7474	0.4829	1.0663	1.3862	56.02	0.7748	1.1495	0.6449	1.0947	1.6242
14	1.325	0.3483	0.7401	0.4713	1.0773	1.4274	54.05	0.8381	1.1555	0.6865	1.1840	[illegible]
15	1.350	0.3370	0.7329	0.4598	1.0890	1.4702	52.14	0.9023	1.1607	0.7287	1.2750	1.6401
16	1.375	0.3255	0.7256	0.4485	1.1016	1.5147	50.29	0.9677	1.1653	0.7717	1.3673	1.6465
17	1.400	0.3142	0.7184	0.4374	1.1149	1.5609	48.50	1.0342	1.1691	0.8154	1.4614	1.6519
18	1.425	0.3033	0.7112	0.4265	1.1291	1.6089	46.76	1.1021	1.1721	0.8601	1.5573	1.6562
19	1.450	0.2927	0.7040	0.4158	1.1440	1.6587	45.07	1.1715	1.1743	0.9057	1.6553	1.6593
20	1.475	0.2824	0.6968	0.4053	1.1597	1.7105	43.42	1.2424	1.1757	0.9523	1.7555	1.6613
21	1.500	0.2724	0.6897	0.3950	1.1762	1.7643	41.81	1.3150	1.1762	1.0000	1.8581	1.6619

.2 9.791 1.958 7.833 NOZLE1 1.

Table 14. Geometrical Parameters of Plug-Nozzles for Selected Nozzle Throat Areas and Ratio of Plug to Nozzle Radii (Tables 14-16 $M_e = 1.5$ $A^* = 15.518\ cm^2$)

EXIT MACH NUMBER: 1.5

EXIT ω : 11.905°

PLUG THROAT REGION PARAMETERS

K= 0.2

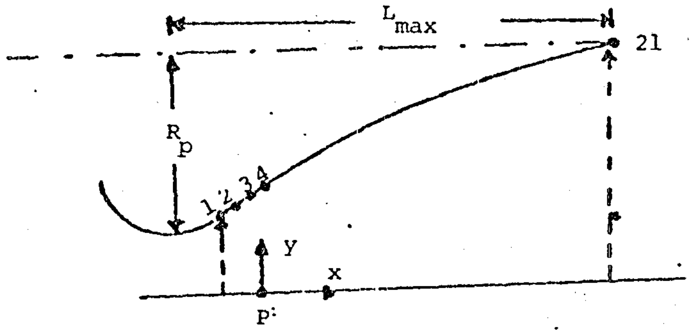
RN= 9.791 CM

RP= 1.958 CM

w_t= 7.833 CM LMAX= 11.916 CM

NO	M	P/PO	T/TO	ρ/ρO	A/A*	r/w_t	φ	x/w_t	y/w_t	L/LMAX	X	Y
1	1.000	0.5283	0.8333	0.6339	1.0000	1.0000	101.91	-0.2043	0.9785	0.0000	-1.6159	[illegible]
2	1.025	0.5130	0.8264	0.6208	1.0005	1.0255	89.05	0.0170	1.0254	0.1468	0.1332	8.0318
3	1.050	0.4979	0.8193	0.6077	1.0020	1.0521	83.67	0.1161	1.0657	0.2119	0.9094	8.1916
4	1.075	0.4830	0.8123	0.5946	1.0045	1.0798	79.50	0.1969	1.0617	0.2650	1.5402	[illegible]
5	1.100	0.4684	0.8052	0.5817	1.0079	1.1087	75.95	0.2692	1.0755	0.3125	2.1085	8.4247
6	1.125	0.4540	0.7980	0.5689	1.0122	1.1388	72.80	0.3367	1.0879	0.3570	2.6377	8.5211
7	1.150	0.4398	0.7908	0.5562	1.0175	1.1701	69.93	0.4015	1.0990	0.3995	3.1448	8.6087
8	1.175	0.4260	0.7836	0.5436	1.0235	1.2026	67.28	0.4646	1.1093	0.4410	3.6300	[illegible]
9	1.200	0.4124	0.7764	0.5311	1.0304	1.2365	64.79	0.5267	1.1187	0.4818	4.1256	8.7672
10	1.225	0.3991	0.7692	0.5188	1.0382	1.2718	62.44	0.5884	1.1275	0.5224	4.6091	8.8314
11	1.250	0.3861	0.7619	0.5067	1.0468	1.3084	60.21	0.6502	1.1355	0.5630	5.0927	[illegible]
12	1.275	0.3733	0.7546	0.4947	1.0561	1.3466	58.07	0.7122	1.1428	0.6037	5.5785	[illegible]
13	1.300	0.3609	0.7474	0.4829	1.0663	1.3862	56.02	0.7748	1.1495	0.6443	6.0636	[illegible]
14	1.325	0.3488	0.7401	0.4713	1.0773	1.4274	54.05	0.8381	1.1555	0.6865	6.5447	9.0566
15	1.350	0.3370	0.7329	0.4598	1.0890	1.4702	52.14	0.9023	1.1607	0.7287	7.0480	9.0990
16	1.375	0.3255	0.7256	0.4485	1.1016	1.5147	50.29	0.9677	1.1653	0.7717	7.5797	9.1277
17	1.400	0.3142	0.7184	0.4374	1.1149	1.5609	48.50	1.0342	1.1691	0.8154	8.1011	9.1575
18	1.425	0.3033	0.7112	0.4265	1.1291	1.6089	46.76	1.1021	1.1721	0.8601	8.6399	[illegible]
19	1.450	0.2927	0.7040	0.4158	1.1446	1.6587	45.07	1.1715	1.1743	0.9057	9.1762	[illegible]
20	1.475	0.2824	0.6968	0.4053	1.1597	1.7105	43.42	1.2424	1.1757	0.9523	9.7317	[illegible]
21	1.500	0.2724	0.6897	0.3950	1.1762	1.7643	41.81	1.3150	1.1762	1.0000	10.3004	9.2129

Table 14a.



EXIT MACH NUMBER : 1.5

EXIT ω : 11.905°

PLUG_THROAT_REGION PARAMETERS

K= 0.2

RN= 9.791 CM

RP= 1.958 CM

W_t= 7.833 CM

Throat Area = 15.518 cm^2
Equivalent to that of a 4.445 cm diameter round nozzle.

LMAX= 11.916 CM

NO	M	X	Y
1	1.000	−1.4159	7.6645
2	1.025	0.1332	8.0318
3	1.050	0.9094	8.1910
4	1.075	1.5422	8.3167
5	1.100	2.1085	8.4247
6	1.125	2.6377	8.5211
7	1.150	3.1448	8.6087
8	1.175	3.6388	8.6891
9	1.200	4.1256	8.7632
10	1.225	4.6091	8.8314
11	1.250	5.0927	8.8942
12	1.275	5.5785	8.9517
13	1.300	6.0686	9.0038
14	1.325	6.5647	9.0506
15	1.350	7.0680	9.0920
16	1.375	7.5797	9.1277
17	1.400	8.1011	9.1575
18	1.425	8.6329	9.1813
19	1.450	9.1762	9.1986
20	1.475	9.7317	9.2093
21	1.500	10.3004	9.2129

.5 12.385 6.192 6.192 NOZLE1 1.5

Table 15.

EXIT MACH NUMBER: 1.5

EXIT ω : 11.905°

PLUG THROAT REGION PARAMETERS

R= 0.5

RU= 12.385 CM

RP= 6.192 CM

W_t= 6.192 CM   LMAX= 9.4199 CM

NO	M	P/PO	T/TO	ρ/ρO	A/A*	r/w_t	φ	X/w_t	Y/w_t	L/LMAX	X	Y
1	1.000	0.5283	0.8333	0.6339	1.0000	1.0000	101.91	-0.2063	0.9795	0.0000	-1.2774	6.0588
2	1.025	0.5130	0.8264	0.6208	1.0005	1.0255	88.05	0.0170	1.0254	0.1468	0.1053	[illegible]
3	1.050	0.4979	0.8193	0.6077	1.0020	1.0521	83.67	0.1141	1.0457	0.2112	[illegible]	[illegible]
4	1.075	0.4830	0.8123	0.5946	1.0045	1.0798	79.50	0.1949	1.0617	0.2456	1.2191	[illegible]
5	1.100	0.4684	0.8052	0.5817	1.0079	1.1092	75.95	0.2692	1.0755	0.3135	1.6660	[illegible]
6	1.125	0.4540	0.7980	0.5690	1.0122	1.1398	72.80	0.3367	1.0879	0.3570	2.0911	6.7336
7	1.150	0.4398	0.7909	0.5562	1.0175	1.1701	69.93	0.4015	1.0990	0.3995	2.4860	6.8052
8	1.175	0.4259	0.7836	0.5436	1.0235	1.2026	67.28	0.4646	1.1093	0.4416	2.8767	[illegible]
9	1.200	0.4124	0.7764	0.5311	1.0304	1.2365	64.79	0.5247	1.1187	0.4816	3.2617	[illegible]
10	1.225	0.3991	0.7692	0.5188	1.0382	1.2718	62.44	0.5884	1.1275	0.5224	3.6635	[illegible]
11	1.250	0.3861	0.7619	0.5067	1.0469	1.3084	60.21	0.6502	1.1355	0.5670	4.0272	[illegible]
12	1.275	0.3733	0.7546	0.4947	1.0561	1.3466	58.07	0.7122	1.1425	0.6037	4.4098	7.0763
13	1.300	0.3609	0.7474	0.4829	1.0663	1.3842	56.02	0.7748	1.1495	0.6449	4.7973	7.1176
14	1.325	0.3488	0.7401	0.4713	1.0773	1.4224	54.05	0.8381	1.1555	0.6865	5.1854	[illegible]
15	1.350	0.3370	0.7329	0.4598	1.0890	1.4702	52.14	0.9023	1.1607	0.7297	5.5877	[illegible]
16	1.375	0.3255	0.7256	0.4485	1.1016	1.5147	50.29	0.9677	1.1653	0.7717	5.9918	7.2154
17	1.400	0.3142	0.7184	0.4374	1.1149	1.5609	48.50	1.0342	1.1691	0.8154	6.4039	[illegible]
18	1.425	0.3033	0.7112	0.4265	1.1291	1.6089	46.76	1.1021	1.1721	0.8601	6.8244	[illegible]
19	1.450	0.2927	0.7040	0.4158	1.1440	1.6587	45.07	1.1715	1.1743	0.9057	7.2533	7.2715
20	1.475	0.2824	0.6968	0.4053	1.1597	1.7105	43.42	1.2424	1.1757	0.9523	7.6930	[illegible]
21	1.500	0.2724	0.6897	0.3950	1.1762	1.7643	41.81	1.3150	1.1762	1.0000	8.1424	[illegible]

.9 27.693 24.924 2.796 NOZLE1 1.5

Table 16.

EXIT MACH NUMBER: 1.5

EXIT ω : 11.905°

PLUG THROAT REGION PARAMETERS

K= 0.9

RP= 27.693 CM

RF= 24.924 CM

W_t = 2.796 CM   LMAX= 4.2535 CM

NO	M	p/PO	T/TO	ρ/ρO	A/A*	r/w_t	ϕ	X/w_t	Y/w_t	L/LMAX	X	Y
1	1.000	0.5283	0.8333	0.6339	1.0000	1.0000	101.91	-0.2063	0.9785	0.0000	-0.5729	[illegible]
2	1.025	0.5130	0.8264	0.6208	1.0005	1.0257	89.05	0.0170	1.0254	0.1449	0.0474	[illegible]
3	1.050	0.4979	0.8193	0.6077	1.0020	1.0521	83.67	0.1141	1.0457	0.2119	0.3244	[illegible]
4	1.075	0.4830	0.8123	0.5946	1.0045	1.0798	79.50	0.1949	1.0617	0.2650	0.5505	[illegible]
5	1.100	0.4684	0.8052	0.5817	1.0079	1.1097	75.95	0.2692	1.0755	0.3125	0.7376	3.0072
6	1.125	0.4540	0.7980	0.5689	1.0122	1.1388	72.80	0.3367	1.0879	0.3570	0.9415	3.0414
7	1.150	0.4399	0.7908	0.5562	1.0175	1.1701	69.93	0.4015	1.0990	0.3995	1.1226	[illegible]
8	1.175	0.4260	0.7835	0.5436	1.0235	1.2026	67.28	0.4646	1.1093	0.4410	1.2992	[illegible]
9	1.200	0.4124	0.7764	0.5311	1.0304	1.2365	64.79	0.5267	1.1177	0.4819	[illegible]	[illegible]
10	1.225	0.3991	0.7692	0.5188	1.0382	1.2718	62.44	0.5884	[illegible]	0.5226	1.6452	3.1504
11	1.250	0.3861	0.7619	0.5067	1.0468	1.3084	60.21	0.6502	1.1355	0.5630	1.8178	3.1738
12	1.275	0.3733	0.7546	0.4947	1.0561	1.3466	58.07	0.7122	1.1428	0.6037	1.9913	3.1953
13	1.300	0.3609	0.7474	0.4829	1.0663	1.3862	56.02	0.7748	1.1495	0.6449	2.1662	3.2139
14	1.325	0.3488	0.7401	0.4713	1.0773	1.4274	54.05	0.8381	1.1555	0.6865	2.3433	3.2304
15	1.350	0.3370	0.7329	0.4598	1.0890	1.4702	52.14	0.9023	1.1607	0.7287	2.5229	[illegible]
16	1.375	0.3255	0.7256	0.4485	1.1016	1.5147	50.29	0.9677	1.1652	0.7717	2.7056	3.2571
17	1.400	0.3142	0.7184	0.4374	1.1149	1.5609	48.50	1.0342	1.1691	0.8154	2.8917	3.2669
18	1.425	0.3033	0.7112	0.4265	1.1291	1.6089	46.76	1.1021	1.1721	0.8601	3.0815	3.2773
19	1.450	0.2927	0.7040	0.4158	1.1440	1.6587	45.07	1.1715	1.1743	0.9057	3.2755	3.2835
20	1.475	0.2824	0.6968	0.4053	1.1597	1.7105	43.42	1.2424	1.1757	0.9523	3.4738	3.2873
21	1.500	0.2724	0.6897	0.3950	1.1762	1.7643	41.81	1.3150	1.1762	1.0000	3.6767	3.2886

5.0671 SIZE .1 .2 .3 .4 .5
v
.5 .6 .7 .8 .9

PLUG THROAT REGION DIMENTIONS
EXIT AREA = 5.0671 SQUARE CENTIMETERS
EQUIVALENT TO A 2.54 CM DIAMETER ROUND nozzle

K	RN CM	RP CM	w_t CM
0.10	3.014	0.301	2.713
0.20	3.197	0.639	2.558
0.30	3.418	1.025	2.392
0.40	3.692	1.477	2.215
0.50	4.044	2.022	2.022
0.60	4.521	2.713	1.809
0.70	5.221	3.655	1.566
0.80	6.394	5.115	1.279
0.90	9.043	8.138	0.904

7.9173 SIZE .1 .2 .3 .4 .5 .6 .7 .8 .9

PLUG THROAT REGION DIMENTIONS
EXIT AREA = 7.9173 SQUARE CENTIMETERS
EQUIVALENT TO A 3.175 CM DIAMETER ROUND nozzle

K	RN CM	RP CM	w_t CM
0.10	4.710	0.471	4.239
0.20	4.995	0.999	3.996
0.30	5.340	1.602	3.738
0.40	5.768	2.307	3.461
0.50	6.319	3.159	3.159
0.60	7.065	4.239	2.826
0.70	8.157	5.710	2.447
0.80	9.991	7.993	1.998
0.90	14.129	12.716	1.413

Table 17. Geometrical Parameters of Plug-Nozzles for Selected Nozzle Throat Areas and Ratio of Plug to Nozzle Radii Tables 17 to 19.

Table 18.

11.401 SIZE .1 .2 .3 .4 .5 .6 .7 .8 .9

PLUG THROAT REGION DIMENTIONS
EXIT AREA = 11.401 SQUARE CENTIMTERS
EQUIVALENT TO A 3.81 CM DIAMETER ROUND nozzle

K	RN CM	RF CM	W_t CM
0.10	6.782	0.678	6.104
0.20	7.193	1.439	5.755
0.30	7.690	2.307	5.383
0.40	8.306	3.322	4.984
0.50	9.099	4.549	4.549
0.60	10.173	6.104	4.069
0.70	11.747	8.223	3.524
0.80	14.387	11.509	2.877
0.90	20.346	18.311	2.035

15.518 SIZE .1 .2 .3 .4 .5 .6 .7 .8 .9

PLUG THROAT REGION DIMENTIONS
EXIT AREA = 15.518 SQUARE CENTIMTERS
EQUIVALENT TO A 4.445 CM DIAMETER ROUND nozzle

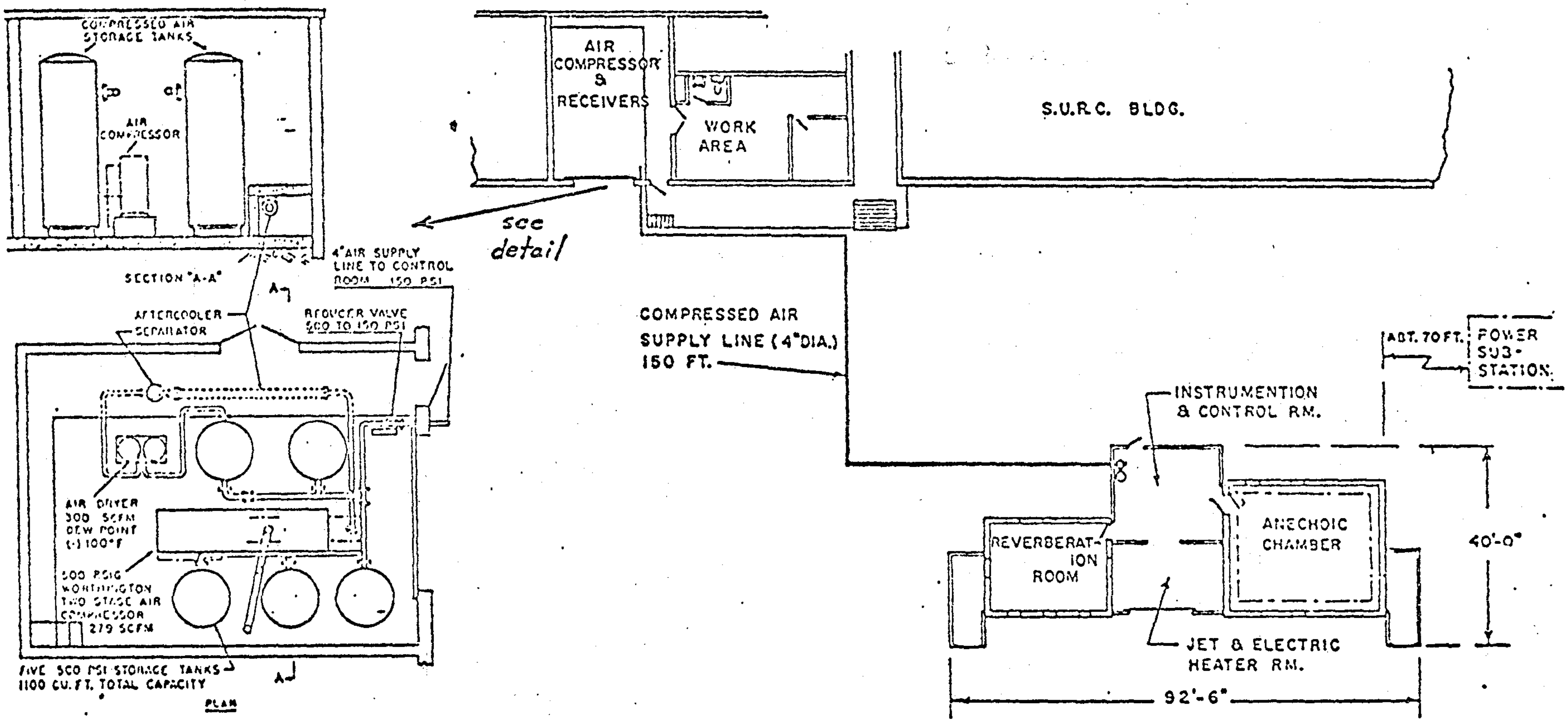
K	RN CM	RF CM	W_t CM
0.10	9.231	0.923	8.308
0.20	9.791	1.958	7.833
0.30	10.467	3.140	7.327
0.40	11.306	4.522	6.783
0.50	12.385	6.192	6.192
0.60	13.847	8.308	5.539
0.70	15.989	11.192	4.797
0.80	19.582	15.666	3.916
0.90	27.693	24.924	2.769

Table 19.

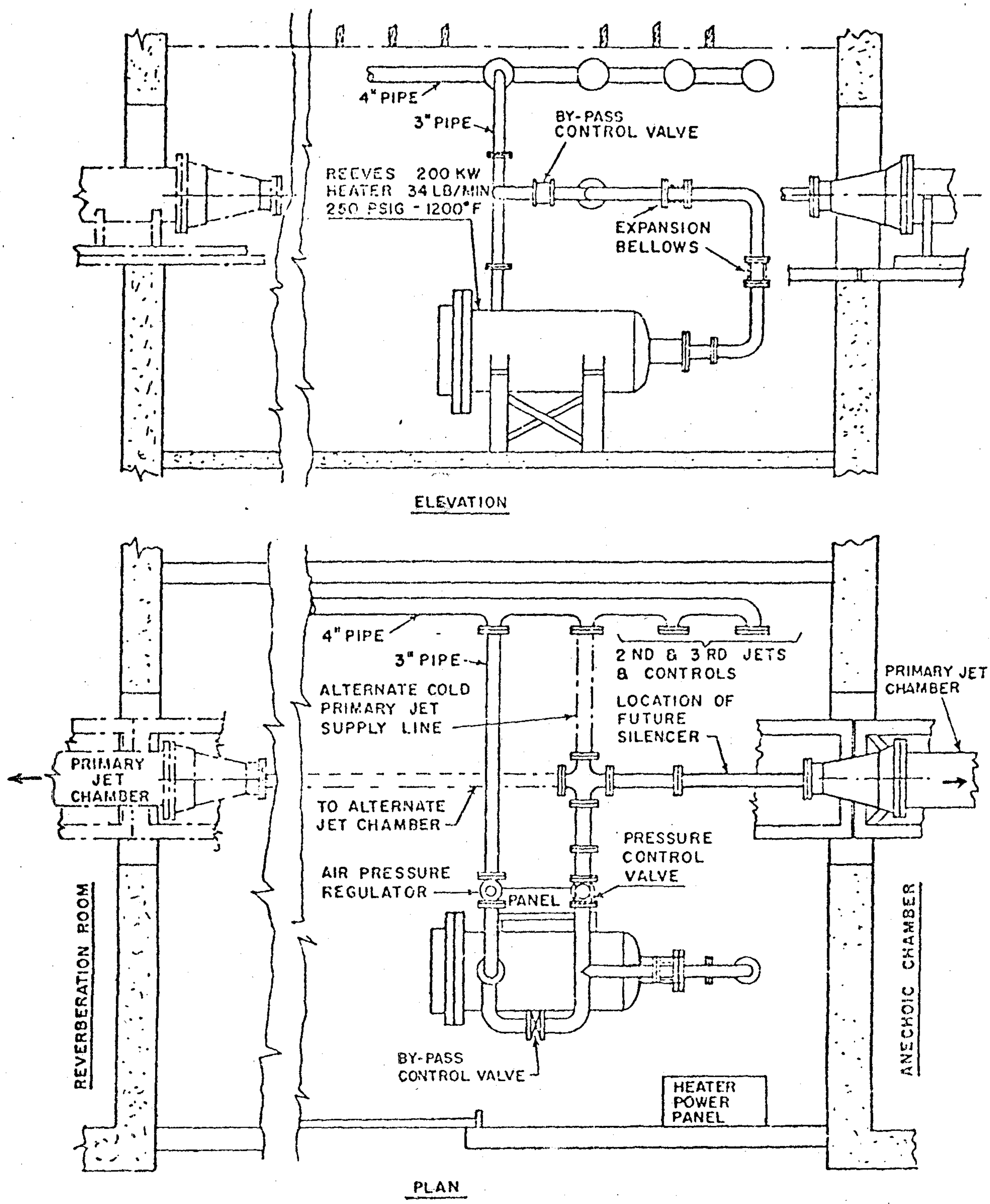
20.268 SIZE .1 .2 .3 .4 .5 .6 .7 .8 .9

PLUG THROAT REGION DIMENTIONS
EXIT AREA = 20.268 SQUARE CENTIMTERS
EQUIVALENT TO A 5.08 CM DIAMETER ROUND nozzle

K	RN CM	RP CM	W_t CM
0.10	12.057	1.206	10.851
0.20	12.788	2.558	10.230
0.30	13.671	4.101	9.570
0.40	14.766	5.907	8.860
0.50	16.176	8.088	8.088
0.60	18.085	10.851	7.234
0.70	20.883	14.618	6.265
0.80	25.576	20.461	5.115
0.90	36.170	32.553	3.617

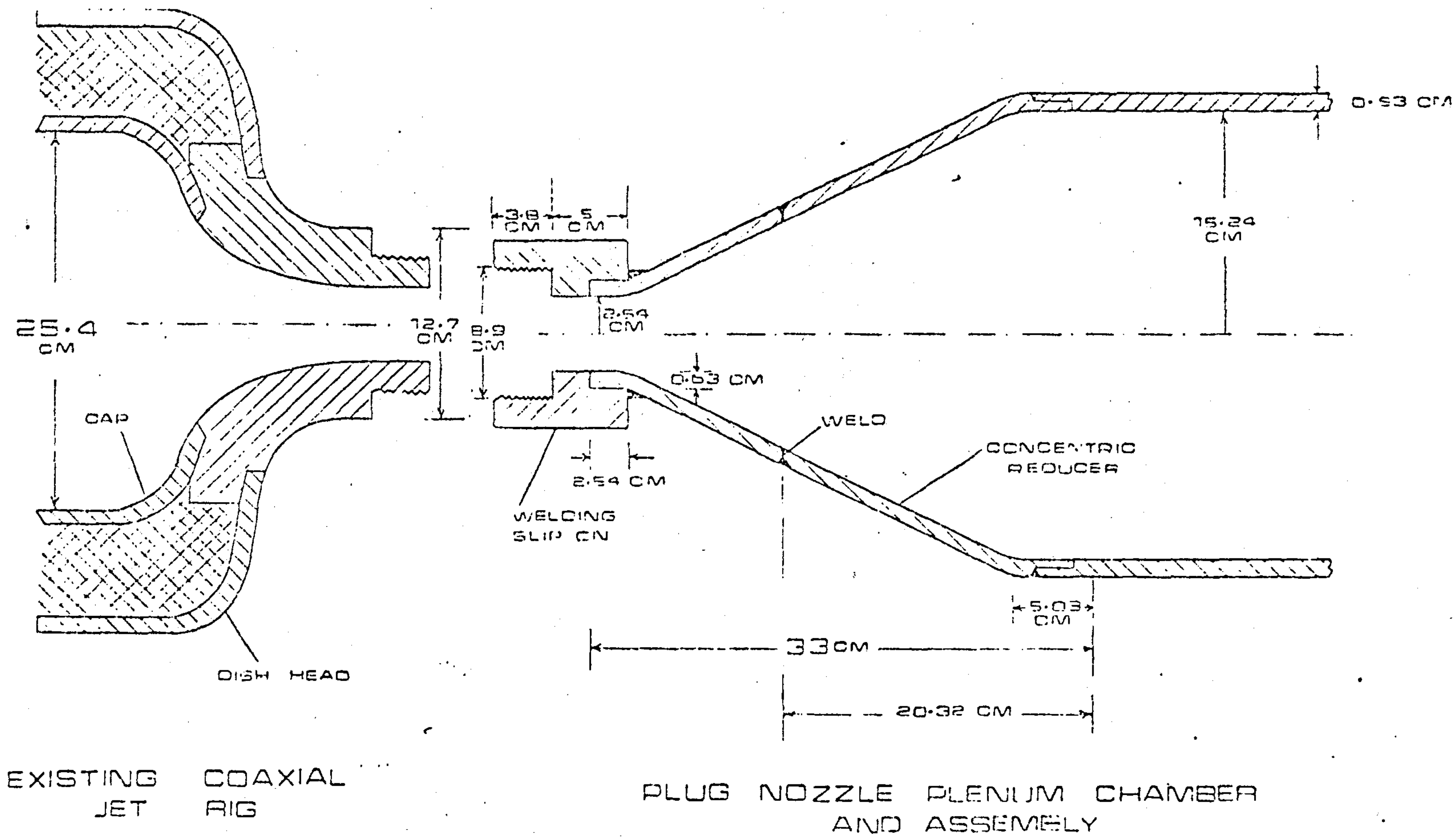


Appendix A. Fig. A1: Compressed Air Supply to the Plug-Nozzle Assembly in the Anechoic Chamber.



Appendix A Fig. A2: Pressure Controls and Supply Chamber for Heated Jet Flows.

Fig. A3.   Supply Chamber for Plug-Nozzles



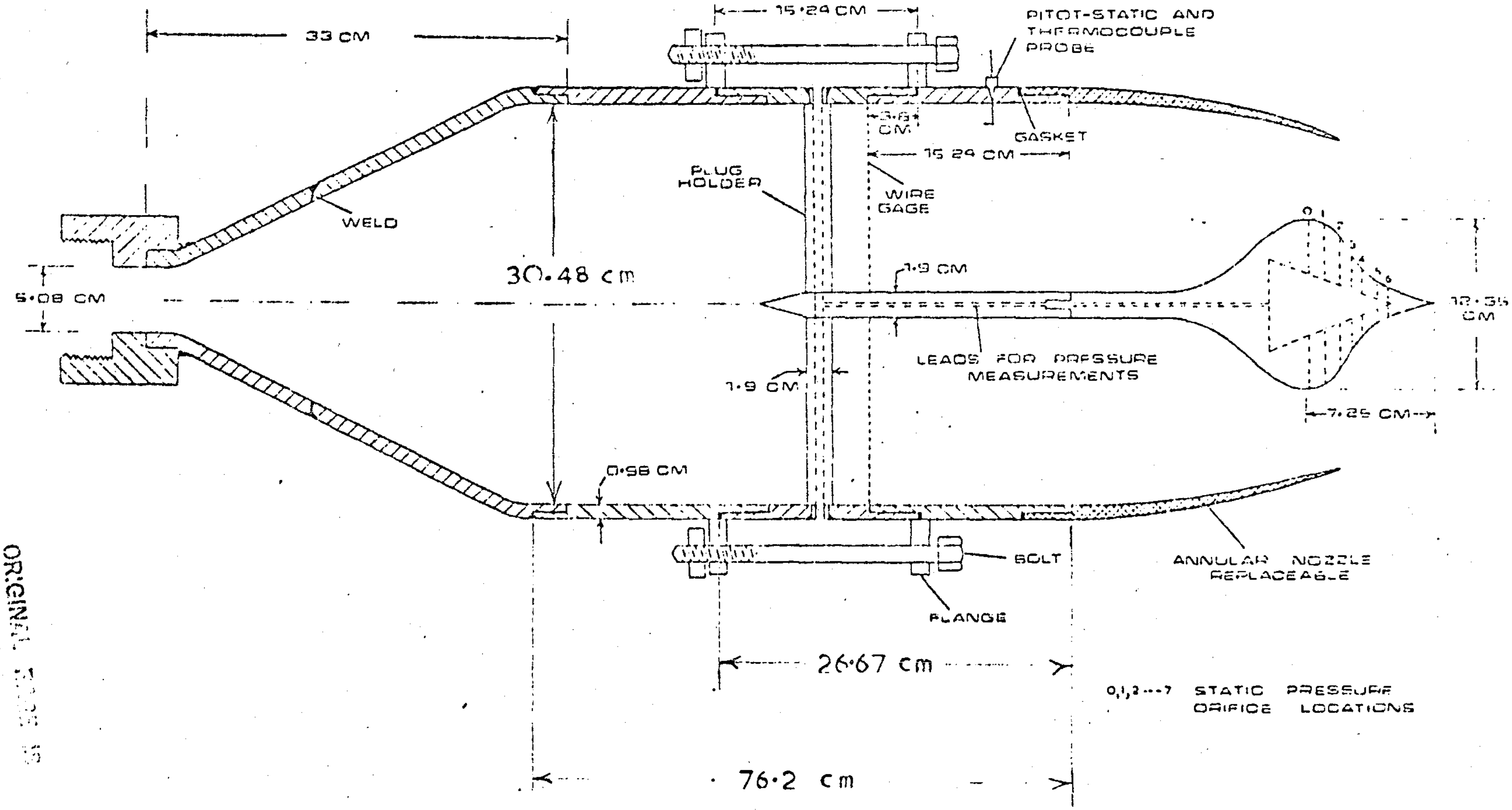


Fig. A4: Plug-Mounting Arrangement in the Plug-Nozzle Throat.

Tables 20-23: Available Run-Times for Choked Plug-Nozzle Flow with Different Throat Areas, Pressure Ratios and Pressure Control Valves.

140 THROAT 12 15 18 21 24 27 30 33 36 39 42 45

2.54 CM CONTROL VALVE 80 PERCENT OPEN
ROUND JET EQUIVALENT DIAMETER = 2.54 CM
PLUG THROAT AREA = 5.0671 SQUARE CENTIMETERS

PO KN/SQUARE METER	ξ	ΔP KN/SQUARE METER	$\dot{M}$ KG/SEC	A SQUARE CM	D CM	T MINUTES	$\dot{M}/\rho$	$\dot{M}c$ KG/SEC	Δt MINUTES
182.8	1.8219	879.5	0.6429	14.8671	4.3513	31.339	0.0432	0.2108	242.83
203.4	2.0274	858.8	0.6412	13.3249	4.1195	31.449	0.0481	0.2435	174.36
224.0	2.2329	838.2	0.6387	12.0514	3.9177	31.612	0.0529	0.2681	136.02
244.6	2.4384	817.6	0.6354	10.9786	3.7392	31.831	0.0578	0.2928	111.49
265.2	2.6438	797.0	0.6313	10.0598	3.5793	32.106	0.0627	0.3175	94.46
285.8	2.8493	776.4	0.6264	9.2618	3.4344	32.441	0.0676	0.3422	81.95
306.4	3.0548	755.8	0.6207	8.5602	3.3018	32.839	0.0724	0.3669	72.36
327.0	3.2603	735.2	0.6142	7.9370	3.1793	33.303	0.0773	0.3915	64.70
347.7	3.4658	714.6	0.6069	7.3783	3.0654	33.838	0.0822	0.4162	58.64
368.3	3.6712	693.9	0.5989	6.8734	2.9586	34.450	0.0870	0.4409	53.56
388.9	3.8767	673.3	0.5902	6.4137	2.8580	35.146	0.0919	0.4656	49.29
409.5	4.0822	652.7	0.5806	5.9927	2.7626	35.933	0.0968	0.4902	45.65

Table 20.

140 THROAT 12 15 18 21 24 27 30 33 36 39 42 45

2.54 CM CONTROL VALVE 80 PERCENT OPEN
ROUND JET EQUIVALENT DIAMETER = 3.175 CM
PLUG THROAT AREA = 7.9173 SQUARE CENTIMETERS

PO KN/SQUARE METER	ξ	ΔP KN/SQUARE METER	$\dot{M}$ KG/SEC	A SQUARE CM	D CM	T MINUTES	$\dot{M}/\rho$	$\dot{M}c$ KG/SEC	Δt MINUTES
182.8	1.8219	879.5	0.6429	14.8671	4.3513	31.339	0.0432	0.3419	82.02
203.4	2.0274	858.8	0.6412	13.3249	4.1195	31.449	0.0481	0.3804	67.98
224.0	2.2329	838.2	0.6387	12.0514	3.9177	31.612	0.0529	0.4190	58.02
244.6	2.4384	817.6	0.6354	10.9786	3.7392	31.831	0.0578	0.4575	50.60
265.2	2.6438	797.0	0.6313	10.0598	3.5793	32.106	0.0627	0.4961	44.87
285.8	2.8493	776.4	0.6264	9.2618	3.4344	32.441	0.0676	0.5346	40.30
306.4	3.0548	755.8	0.6207	8.5602	3.3018	32.839	0.0724	0.5732	36.57
327.0	3.2603	735.2	0.6142	7.9370	3.1793	33.303	0.0773	0.6118	33.48
347.7	3.4658	714.6	0.6069	7.3783	3.0654	33.838	0.0822	0.6503	30.87
368.3	3.6712	693.9	0.5989	6.8734	2.9586	34.450	0.0870	0.6889	28.64
388.9	3.8767	673.3	0.5902	6.4137	2.8580	35.146	0.0919	0.7274	26.70
409.5	4.0822	652.7	0.5806	5.9927	2.7626	35.933	0.0968	0.7660	25.02

Table 21

140 THROAT 12.15 18 21 24 27 30 33 36 39 42 45

5.08 CM CONTROL VALVE 80 PERCENT OPEN
ROUND JET EQUIVALENT DIAMETER = 5.08 CM
PLUG THROAT AREA = 20.268 SQUARE CENTIMETERS

PO KN/SQUARE METER	ξ	ΔP KN/SQUARE METER	Ṁ KG/SEC	A SQUARE CM	D CM	T MINUTES	Ṁ/A	Ṁc KG/SEC	Δt MINUTES
182.8	1.8219	879.5	1.8464	42.6972	7.3741	9.028	0.0432	0.8752	21.22
203.4	2.0274	858.8	1.8401	38.2394	6.9785	9.061	0.0481	0.9739	18.66
224.0	2.2329	838.2	1.8316	34.5597	6.6343	9.107	0.0529	1.0726	16.65
244.6	2.4384	817.6	1.8208	31.4615	6.3299	9.166	0.0578	1.1713	15.03
265.2	2.6438	797.0	1.8079	28.8095	6.0573	9.238	0.0627	1.2700	13.70
285.8	2.8493	776.4	1.7927	26.5073	5.8102	9.324	0.0676	1.3687	12.58
306.4	3.0548	755.8	1.7753	24.4846	5.5841	9.424	0.0724	1.4674	11.64
327.0	3.2603	735.2	1.7557	22.6889	5.3754	9.539	0.0773	1.5661	10.82
347.7	3.4658	714.6	1.7340	21.0800	5.1814	9.670	0.0822	1.6648	10.11
368.3	3.6712	693.9	1.7102	19.6269	4.9996	9.819	0.0870	1.7635	9.47
388.9	3.8767	673.3	1.6843	18.3051	4.8283	9.985	0.0919	1.8622	8.94
409.5	4.0822	652.7	1.6564	17.0952	4.6660	10.171	0.0968	1.9609	8.45

Table 22.

140 THROAT 12 15 18 21 24 27 30 33 36 39 42 45

5.08 CM CONTROL VALVE 80 PERCENT OPEN
ROUND JET EQUIVALENT DIAMETER = 4.445 CM
PLUG THROAT AREA = 15.518 SQUARE CENTIMETERS

PO KN/SQUARE METER	ξ	ΔP KN/SQUARE METER	Ṁ KG/SEC	A SQUARE CM	D CM	T MINUTES	Ṁ/A	Ṁc KG/SEC	Δt MINUTES
182.8	1.8219	879.5	1.8464	42.6972	7.3741	9.028	0.0432	0.6701	29.68
203.4	2.0274	858.8	1.8401	38.2394	6.9785	9.061	0.0481	0.7456	25.88
224.0	2.2329	838.2	1.8316	34.5597	6.6343	9.107	0.0529	0.8212	22.94
244.6	2.4384	817.6	1.8208	31.4615	6.3299	9.166	0.0578	0.8968	20.60
265.2	2.6438	797.0	1.8079	28.8095	6.0573	9.238	0.0627	0.9723	18.69
285.8	2.8493	776.4	1.7927	26.5073	5.8102	9.324	0.0676	1.0479	17.11
306.4	3.0548	755.8	1.7753	24.4846	5.5841	9.424	0.0724	1.1235	15.77
327.0	3.2603	735.2	1.7557	22.6889	5.3754	9.539	0.0773	1.1991	14.63
347.7	3.4658	714.6	1.7340	21.0800	5.1814	9.670	0.0822	1.2746	13.64
368.3	3.6712	693.9	1.7102	19.6269	4.9996	9.819	0.0870	1.3502	12.78
388.9	3.8767	673.3	1.6843	18.3051	4.8283	9.985	0.0919	1.4258	12.02
409.5	4.0822	652.7	1.6564	17.0952	4.6660	10.171	0.0968	1.5013	11.34

Table 23.

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